

**Development and application of a multi-criteria decision-support
framework for planning rural energy supply interventions in low-income
households in South Africa**



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ABSTRACT

Problems in the public policy decision-making environments are typically complex and continuously evolve. In a resource-constrained environment, several alternatives, criteria, and conflicting objectives must be considered. As a result, solutions to these types of problems cannot be modelled solely using single-criteria techniques. It has been observed that most techniques used to shape energy policy and planning either produce sub-optimal solutions or use strong assumptions about the preferences of decision-maker(s). This difficulty creates a compelling need to develop novel techniques that can handle several alternatives, multiple criteria and conflicting objectives to support public sector decision-making processes. First, the study presents a novel scenario-based multi-objective optimisation framework based on the augmented Chebychev goal programming (GP) technique linked to a value function for analysing a decision environment underlying energy choice among low-income households in isolated rural areas and informal urban settlements in South Africa. The framework developed includes a multi-objective optimisation technique that produced an approximation of a Pareto front linked to an *a priori* aggregation function and a value function to select the best alternatives. Second, the study used this model to demonstrate the benefits of applying the framework to a previously unknown subject in public policy: a dynamic multi-technology decision problem under uncertainty involving multiple stakeholders and conflicting objectives. The results obtained suggest that while it is cost-optimal to pursue electrification in conjunction with other short-term augmentation solutions to meet South Africa's universal electrification target, sustainable energy access rates among low-income households can be achieved by increasing the share of clean energy generation technologies in the energy mix. This study, therefore, challenges the South African government's position on pro-poor energy policies and an emphasis on grid-based electrification to increase energy access. Instead, the study calls for a portfolio-based intervention. The study advances interventions based on micro-grid electrification made up of solar photovoltaics (PV), solar with storage, combined cycle gas turbine (CCGT) and wind technologies combined with either bioethanol fuel or liquid petroleum gas (LPG). The study has demonstrated that the framework developed can benefit public sector decision-makers in providing a balanced regime of technical, financial, social, environmental, public health, political and economic aspects in the decision-making process for planning energy supply interventions for low-income households. The framework can be adapted to a wide range of energy access combinatorial problems and in countries grappling with similar energy access challenges.

Keywords: energy access, multi-objective linear programming, multi-criteria decision analysis, augmented Chebychev goal programming, multi-attribute value theory, low-income households, dynamic multi-technology decision problem under uncertainty, scenario analysis, sensitivity analysis, isolated rural areas and informal settlements.

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LIST OF ABBREVIATIONS

<i>PM</i> _{2.5}	Fine Particulate Matter
AHP	Analytic Hierarchy Process
BCA	Benefit-cost Analysis
CCGT	Combined Cycle Gas Turbine
CEA	Cost-effectiveness analysis
CEA	Cost-effectiveness Analysis
COGTA	Department of Cooperative Governance and Traditional Affairs
COJMM	City of Johannesburg Metropolitan Municipality
CPI	Consumer Price Index
CSP	Concentrating Solar Power
CTMM	City of Cape Town Metropolitan Municipality
DHS	Department of Human Settlements
DMRE	Department of Mineral Resources and Energy formerly DOE
DOE	Department of Energy (South Africa)
DRDLR	Department of Rural Development and Land Reform
DST	Department of Science and Technology
EBSST	Electricity Basic Service Support Tariff
EIA	Environmental impact assessments
ELECTRE	Elimination Choice Translating Reality
EMM	Ekurhuleni Metropolitan Municipality
ERC	Energy Research Centre
FBAE	Free Basic Alternative Energy
FBE	Free Basic Electricity
GEAR	Growth, Employment and Redistribution
GHS	General Household Survey
GJ	Gigajoule
GP	Goal Programming

GTAC	Government Technical Advisory Centre
HESASA	Household Energy Safety Association of Southern Africa
IBT	Inclining Block Tariff
IDP	Integrated Development Plan
IEA	International Energy Agency
IEP	Integrated Energy Plan
INEP	Integrated National Electrification Programme
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRP	Integrated resource plan
kWh	kilowatt-hour
MACBETH	Measuring Attractiveness by a Categorical Based Evaluation Technique
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-attribute value theory
MCDA	Multi-criteria decision analysis
MFMA	Municipal Finance Management Act (Act 56 of 2003)
MISA	Municipal Infrastructure Support Agent
MOLP	Multiple Objective Linear Programming
MULTIMOORA	Multi-Objective Optimization based on Ratio Analysis
NDOH	National Department of Health
NDP	National Development Plan
NEP	National Electrification Programme
NSWHP	National Solar Water Heater Programme
NSWHP	National Solar Water Heater Programme
OCGT	Open Cycle Gas Turbine
OECD	Organisation for Economic Co-operation and Development
PAIRS	Preference Assessment by Imprecise Ration Statements
PASASA	Paraffin Safety Association of Southern Africa

PESTEL	Political, Economic, Social, Technological, Environmental and Legal
PROMETHEE	Preference Ranking Organisation Method for Enrichment of Evaluations
PV	Photovoltaics
R	The South African Rand, the lawful currency of the Republic of South Africa
REIPPPP	Renewable Energy Independent Power Producer Procurement Program
SABS	South African Bureau of Standards
SAL	Small Area Layer
SDG	Sustainable Development Goal
SHS	Solar Home Systems
SMART	Simple Multi-Attribute Rating Technique
Stas SA	Statistics South Africa
SUREDSS	Sustainable Rural Energy Decision Support System
TOPSIS	The Technique for Order Preference by Similarity to Ideal Solutions
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
V.I.S.A	Visual Interactive Sensitivity Analysis
CO_2	Carbon Dioxide

CHAPTER 1

INTRODUCTION TO THE STUDY

“Energy is essential to many human activities and is crucial to the socio-economic development of a country” Integrated Energy Plan 2013

1.0 Chapter introduction

Chapter 1 presents the introduction and background of the research study and covers the study objectives. The section also provides the scope and significance of the study. The practical value of the study to stakeholders involved in the energy, poverty and development environment in the public sector is also presented. The chapter concludes with study limitations and a brief overview structure and the adopted scientific method.

1.1 Background of the study

Access to energy is central to humanity and development. The development of many societies throughout history is closely linked to access to modern energy sources. The discovery of fossil fuels and electricity in the late 19th century led to many Western European countries and North America's successful industrialisation and economic prosperity. (Dobbs et al., 2015). This discovery led to the introduction of diesel and electric-powered machine tools and electric lighting in factories. These developments were central to improvements in mobility, working conditions and productivity. Despite all these patent improvements brought about by fossil fuel-based energy and electrification, it is sad to note that some households and communities in South Africa and the developing world continue to rely on rudimentary energy sources more than a century later. The situation is further exacerbated by a lack of access to basic needs like food, water and sanitation, housing, mobility and information. Global warming has changed weather patterns and poor rains, affecting yields and further entrenching poverty.

According to Zhou et al. (2008), the energy status of rural households globally presents an extensive index indicating rural socio-economic and living standards. Many people spend much time on unproductive activities such as collecting fuels (see Exhibit 1). Collecting fuel is commonly considered a women's duty (Dovie et al., 2004; Howells et al., 2005; Matinga and Annegarn, 2013). Recently, according to (Urge and Feyisa, 2019), in Ethiopia, among family members involved in fuel collection, 51 per cent is shared by mothers, 36 per cent by girls, eight per cent by boys and five per cent by fathers. This disparity has meant that women and young girls remain in the throes of poverty, given the lack of access to education and

productive and non-participation in income-generating employment activities (Kaygusuz, 2010).

In 2008, Kanagawa and Nakata (2008) postulated that access to modern sources of energy results in poverty eradication and development (Kanagawa and Nakata, 2008). Most researchers have concluded that among the most vulnerable poor households, energy security is crucial in the fight against poverty and is an essential ingredient for sustainable development (Starr, 1996, Pachauri and Spreng, 2004; Van der Kroon et al., 2013). The United Nations Industrial Development Organisation (UNIDO) underscored these empirical arguments and

Exhibit 1: Common sight in a rural village of Cutwini, Eastern Cape



Source: Matinga (2013)

concluded in 2015 that “energy is an essential factor for sustainable development and poverty eradication”. Similarly, the World Bank noted that “access to affordable, reliable and sustainable energy is vital to driving economic growth and ending extreme poverty” (World Bank, 2016).

According to Statistics South Africa (Stats SA), approximately a third of South Africans live in rural and informal urban areas. (Stats SA, 2019). These areas house some of the poorest people in the country. While it is acknowledged that significant headways have been made to improve access to energy through rural electrification, the Department of Mineral Resources and Energy (DMRE) statistics show that, in 2018, an estimated 2.2 million homes remained unconnected to the central grid in the country (DMRE, 2018). Many people rely on solid fuels, kerosene and other rudimentary forms of energy for cooking.

According to Madubansi and Shackleton (2006), while electricity use increased for lighting and powering media appliances in households with access to electricity (84.2%), firewood remained the primary energy source for heating and cooking. As a result, the proportion of households purchasing firewood increased between 1991 and 2002 (Madubansi and Shackleton, 2006). Electricity has the disadvantage that it is unaffordable to many households. In addition, the cost of electrical appliances is beyond the means of most families, especially those who solely depend on social grants (Bhorat et al., 2012; Stats SA, 2019).

According to the 2019 Stats SA's Non-Financial Census of Municipalities Report, in 18 municipalities, over 61 000 indigent households (1.7 per cent of the 3.6 million indigent households nationwide) are supplied with free kerosene. Sixteen of these municipalities are in the Eastern Cape and Northern Cape provinces. The use of candles for lighting is also prevalent in South Africa. According to the 2018 General Household Survey (GHS) Report, approximately five per cent of the country's 16.6 million households rely on candles for lighting (Stas SA, 2019).

1.2 The problem

According to the World Health Organisation (WHO), as of 2018, nearly three billion people rely on rudimentary solid fuels such as firewood and kerosene for cooking (WHO, 2018). Cooking with open fires using dirty fuels poses high health risks owing to high levels of household air pollution (HAP) exposure. According to the WHO, HAP accounts for nearly 3.8 million premature deaths annually (WHO, 2018). According to the 2019 Global Burden of Disease Report, many developing countries are affected by respiratory diseases such as adverse pregnancy outcomes, child pneumonia, heart diseases, lung cancer and eye cataracts (Pokhrel et al., 2005; Dherani et al., 2008, Kurmi et al., 2010, Kurmi et al., 2012; Amegah et al., 2014; Dutta et al., 2017; and Arku et al., 2018; Jung and Huxham, 2019; Soriano et al., 2020).

Two independent studies by Nautiyal (2013) and Singh et al. (2017) in India established that deforestation in the two different areas of the study areas was attributed to the indiscriminate and unsustainable cutting down of trees for firewood. Deforestation causes people to spend more time collecting firewood as a result of the increased travel time, resulting in lost income and poverty. It was against this background that scholars (Brooks et al., 2016; Van der Kroon et al., 2013; Northcross et al., 2016) posited that modern fuels are a vital ingredient for socio-economic development and prosperity. Following the "the energy ladder" postulate (Van der Kroon et al., 2013), it is expected that replacing rudimentary fuels with cleaner fuels will result in time and fuel savings and, in the process, free time available for productive economic activities.

According to Johnson and Chiang (2015) and the Institute of Race Relations (2016), a switch from polluting fuels to clean¹ cooking fuels is needed to achieve improvements in health outcomes through a reduction in HAP exposures below WHO guidelines. Such a switch will

¹ Fuels that produce fewer greenhouse emissions.

lead to the achievement of Sustainable Development Goals² (SDGs) (United Nations, 2015). For instance, a recent cohort study of 280 000 Chinese never-smokers in China by Lawson et al. (2019) established a significant reduction in the risk of major respiratory diseases when households switched from polluting to clean primary cooking fuels

Despite government efforts to electrify all households in rural South Africa, there is still a huge backlog. Many families continue to rely on rudimentary forms of energy. The backlog is attributed to grid extension limitations. For example, South African law prohibits Eskom⁵ from extending the grid to informal settlements located on privately owned and proclaimed land. At the same time, despite electrification, many low-income families are not utilising electricity for meeting energy needs owing to irregular and erratic cash flows. This results in households procuring energy in small units. In most instances these households are forced to rely on cheaper energy options such as candles, paraffin and firewood.

Tackling energy poverty in South Africa is thus a multifaceted problem that requires new thinking and solutions that cater for all. Various programmes aimed at increasing energy access for low-income households, such as the Solar Home Systems (SHS) programme, are also being considered. Strategic decisions need to be taken for the development of a desirable energy mix for different energy uses among low-income families. The problem addressed in this study was that of selecting a portfolio of energy supply alternatives for low-income households while accounting for sustainability.

A community in the context of this study was defined as a group of people living in the same place with a particular characteristic (poverty) in common. These communities are located in areas identified by Hughes et al. (2017) and discussed in Section 2.2. This study was linked to the United Nation's SDG 7 and was anchored on the understanding that households do not consume energy for the sake of consuming it but do so because of what services energy provides. SDG 7 aims "to ensure universal access to affordable, reliable and modern energy services by 2030" (United Nations, 2015).

Energy is needed for the day-to-day functioning of any household, from cooking, space heating and lighting to the running of electrical appliances such as radios and televisions (UNDP, 2000). Also, energy is essential for income generation activities such as agriculture and the operation of micro-enterprises..

² The Sustainable Development Goals (SDGs) are 17 global goals of the United Nations designed to be a "blueprint for achieving a better and more sustainable future for all" (United Nations, 2015).

⁵ Eskom is a state-owned electricity company in South Africa.

Many households rely on traditional and inefficient fuels such as firewood, candles and kerosene. Family members spend a considerable amount of time collecting and preparing firewood. High moisture content during the summer season decreases the usefulness of firewood, leaving many households to depend on kerosene and other rudimentary forms of energy. In South Africa, between three and four million households remained off the grid (Institute of Race Relations, 2016). Harmful kerosene and firewood still dominate the South African energy market among poor households owing to the relative affordability and availability of these fuels (Stats SA, 2019). As summarised in Table 1, continued dependence on dirty fuels poses serious health, environmental and socio-economic costs for South Africa.

Table 1: Impact of using dirty fuel for cooking

Risk	Impact
Health	<ul style="list-style-type: none"> ▪ Indoor air pollution: 2 500 deaths annually (Norman et al., 2007), indoor air pollution accounts for the deaths of 1,400 South African children per year (Barnes et al.,2009), likely a substantial underestimate of the full disease burden as many negative cooking health effects have not yet been quantified (e.g., burns, eye diseases, physical injuries from carrying firewood, etc.). In 2012, kerosene related fires are known to have resulted in injuries and lost property affecting nearly 200 000 in South Africa every year (Kimemia et al., 2014). ▪ Acute lower respiratory infections are among the four top killers of South Africans under the age of five, largely due to indoor air pollution (Barnes et al.,2009).
Environment	<p>Deforestation and forest degradation: South Africa loses substantial amounts of wood from its forests every year from illegal and unsustainable fuelwood extraction, a major contributor to deforestation (Berry et al, 2005; Wessels et al, 2013; Carte Blanche (2020a, 2020b). Household fuel use in South Africa contributes to GHG emissions.</p>
Food security	<p>Food insecurity: deforestation, resulting from the use of dirty fuels, exacerbates food insecurity and harms the agriculture sector.</p>

Source: Norman et al. (2007), Barnes et al. (2009) Berry et al. (2005), Wessels et al (2013), Kimemia et al (2014), Carte Blanche (2020a, 2020b)

Households with access to grid electricity still face challenges and rarely make maximum use of it due to the high costs of appliances and electricity. In some instances, cultural beliefs also render the use of grid electricity impractical. Those households with solar power receive

intermittent power during low sunshine periods and no power at night. These periods can be as long as two months during the rainy season. Theft of rooftop solar systems has also rendered this option inoperable in some low-income areas. In some cases, these systems are just considered inappropriate and are not used for several reasons, such as cultural beliefs. According to Sovacool and Griffiths (2019), “no matter how well developed or perfected a given energy technology or energy system becomes in a laboratory, it could have little to no impact without systematic and scientific efforts to ensure such technologies are culturally compatible.”

Given the vast chasm in the provision of affordable and reliable energy, many households are forced to resort to the use of multiple energy sources. Energy access for low-income families thus typifies an energy portfolio problem. For the study, an energy portfolio was defined as a set of projects for implementation for a low-income community living in isolated rural areas. The selection of the appropriate portfolio must meet goals without violating constraints. Three difficulties arise in selecting the appropriate portfolio. These three difficulties include multiple goals, uncertainty and the availability of too many feasible options.

In 2002, Belton and Stewart branded portfolio selection as *problematique*⁶ to which Multi-criteria Decision Analysis (MCDA) technique can be applied (Belton and Stewart, 2002). According to Belton and Stewart (2002), the portfolio consists of choosing a subset of alternatives from a wide range of possibilities. The portfolio construction process considers the characteristics of the options individually and tests how the alternatives interact together with their positive or negative synergies. Synergies carry the notion of cooperation between parts. Synergy exists between alternatives if the total value of the portfolio containing the alternatives is greater than the sum of the project’s values (Belton and Stewart, 2002).

1.3 Motivation for the present study

The motivation for the present study can be traced to four key government of South Africa energy planning policy pronouncements, namely the Electricity Basic Service Support Tariff (EBSST), Integrated Resources Plan (IRP), the Integrated National Electrification Programme (INEP), the Free Basic Electricity (FBE), the Free Basic Alternative Energy (FBAE) and the SHS. These policies provide guidance and direction for on and off-grid investments and energy access support at the national and sub-national levels.

⁶ The complex issues associated with a topic, considered collectively; specifically, the totality of environmental and other problems affecting the world.

The adoption of energy efficiency measures and renewable energy technologies has not gained widespread traction in South Africa. Illegal electricity connections in formal and informal settlements continue unabated (Seleka, 2021). The study posits a wide range of modern energy supply technologies that may be implemented to increase energy access among low-income households in the country. Therefore, new thinking, anchored on homegrown solutions, is needed to unravel the problem of access to energy and poverty eradication. For example, Bhattacharyya (2012) argues that there has been an unbalanced emphasis on rural electrification over the past decades, which has sadly failed to solve the energy access problem and augment sustainable development pursuits.

A review of the energy access policies revealed the multi-objective nature and multi-actor features of energy resource planning. Two main branches of objectives can be identified: tangible objectives, primarily economic and technical and intangible goals, such as social and externalities. The energy access planning problem in South Africa, therefore, lends itself well as the right candidate for a multi-criteria decision-making problem as several interest groups characterise the problem with different objectives to which a hierarchy of criteria can be developed.

1.4 Research objectives

This thesis aimed **to develop and validate an alternative and evidence-based decision-making procedure based on MCDA techniques for planning energy supply interventions among low-income households in South Africa**. It is expected that, if adopted, the framework will aid the public sector decision-makers when evaluating strategies aimed at increasing access to energy among low-income households living in isolated rural and informal urban areas.

The study was also aimed at achieving the following secondary objectives:

- i) Evaluation of the current state of the energy supply situation in South Africa among low-income families;
- ii) Review of empirical literature on MCDA and its application to energy supplies problems;
- iii) Development of an alternative decision-making procedure for selecting a portfolio of energy supply technologies for low-income households in South Africa;
- iv) Validation of the framework developed and a demonstration of how the use of MCDA tools could aid rural development stakeholders with effective policy making; and

-
- v) Presentation of policy recommendations to support future stakeholder decision-making processes.

To this end, a framework developed for the study was used. Both the procedure developed, its application and the solutions presented were demonstrated.

1.5 Significance

This research is the first study known to the author that comprehensively analyses the broader implications of selecting one rural energy supply portfolio over another among low-income households while taking sustainable development into account. There is no evidence of the use of MCDA techniques for planning energy access among low-income households in South Africa.

On the academic side, the few studies that have been conducted in South Africa that employ MDA techniques focused mainly on mining sector investments (Esteves, 2008), environmental impact assessments, forest management (Joubert al, 1997); water supply management (Pietersen, 2006), water resources planning (Stewart and Scott, 1995) transport, (Notteboom, 2011); and energy infrastructure (Petrie et al., 2004) infrastructure investments in general. On the international stage, work has been done in sectoral areas such as water, transport and rural energy infrastructure with emphasis on the use of the Analytic Hierarchy Process (AHP) and unpacked focusing specifically on energy access among the poor.

According to Bouyssou et al. (1993), in their work "The manifesto of the new MCDA era", proposed areas for further research in MCDA included addressing the critical theoretical and methodological issues relating to MCDA. Bouyssou et al. (1993) also recommended exploring new topics of applications and the use of MCDA techniques in ex-post analysis. The connection between MCDA and other areas of research needs to be investigated, according to Bouyssou et al. (1993).

The study brought together rural and energy development policy issues of contemporary significance. While rural development and water and energy policies are being developed, there appears to be little understanding of the implications of the different courses of action. The study resulted in the development of a problem structuring framework that, if implemented, is expected to improve the current and future thinking and understanding of rural energy infrastructure development matters. The procedure offers energy and rural development stakeholders the inputs needed in the development of more integrated policies.

The study will also contribute to the low-income energy supply literature by proposing a comprehensive list of relevant evaluation criteria for energy supply technologies and constructing a logical, hierarchical structure of these elements.

This application of multi-objective linear programming techniques to combinatorial problems offers innovative insights into the applicability to real-life, complex decision problems. Combinatorial problems involve finding a grouping, ordering, or assignment of a discrete, finite set of objects that satisfies given conditions. Candidate solutions are combinations of solution components that may be encountered during a solution attempt but do not have to meet all the provided criteria. The study potentially emphasises the MCDA advantages over competing approaches. Also, with regards to the low-income household energy access policymaking, this application is unprecedented.

Beneficiaries of the study are the public sector and non-governmental institutions seized with the designing, crafting, evaluation and implementation of energy access and development policies. The study recommendations, if embraced, should help reduce reliance on one-dimensional and monetary techniques and present an opportunity to explore the use of non-monetary evaluations.

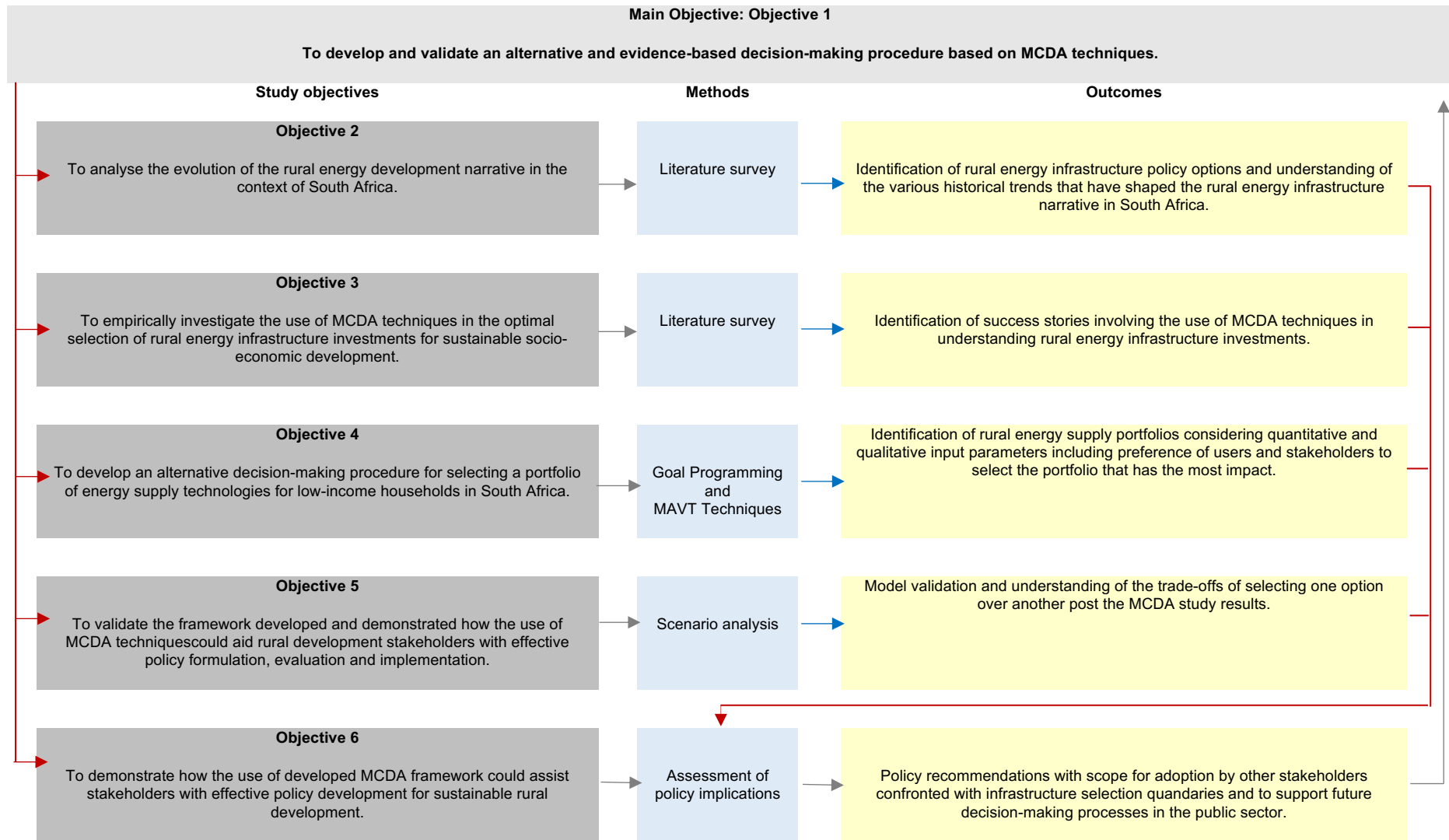
The debate on the nexus between energy access and sustainable rural development has primarily focused on quantifying rural energy infrastructure demand with a strong emphasis on rural electrification. There is scope for developing sectoral and national energy planning and decision-making, and this is what the study was designed to achieve.

1.6 Research framework

An important part of the research process was the formulation of a formal problem-solving approach as described by Rosenhead and Mingers (2001) and later by Belton and Stewart in 2002 and 2010. Belton and Stewart (2010) best describe the link between MCDA and problem structuring.

Figure 1 summarises the methodological research framework developed for this study. The research framework was based on research methods drawn from several academic disciplines on the use of MCDA techniques. This research framework comprises literature review, historical analysis, scenario analysis and an assessment of policy implications.

Figure 1: Methodological framework for this research



1.7 Research methods

This section presents the research methods that were adopted for the study. The methods syndicated both qualitative and quantitative research methods.

1.7.1 A review of the status quo

A review of the status quo was used to establish the status quo and develop a historical time profile of South African rural energy development and development interventions. The purpose of the historical analysis was to identify the current energy policies and supply options and the forces that have shaped the development of the rural energy infrastructure in the country, given the historical imbalances.

1.7.2 Literature survey

A literature survey was employed to substantiate research findings as well as interrogate the theoretical and methodological contributions of the application of MCDA techniques to confront rural energy development problems. The literature survey was based on secondary sources of information, including academic publications and journals. The theoretical and empirical literature reviews for the study are presented in Chapter 3 and Chapter 4.

1.7.3 Goal programming and multi-attribute value theory

The research developed a multi-objective optimisation framework based on the augmented Chebychev goal programming (GP) and MAVT techniques to analyse the decision environment underlying energy choices among low-income households in South Africa.

1.7.4 Scenario analysis

Scenario analysis was employed to assess the various alternative energy supply portfolios that satisfy the target objective of maximising sustainable rural economic growth and development. The scenario that closely aligns with the intended objective was modelled and born out of the multi-objective optimisation framework developed.

1.8 Scope of research

The scope of the research varied for specific objectives and was dependent on the availability of suitable data. This scope was defined as temporal, spatial and sectoral, as outlined in Table 2. The primary spatial scope of this research was the isolated rural and informal urban areas of South Africa.

Table 2: Research scope

Specific Objective	Research Method	Temporal	Spatial	Sectoral
1	Literature survey	Pre and post-apartheid era	National, rural and peri-urban settlements	Electricity industry and development sector
2	Literature survey	1990 – 2021	National, rural and peri-urban settlements	Electricity industry and development sector
3	MAVT	2017 – 2021	National, rural and peri-urban settlements	Electricity industry and development sector
4	Scenario analysis	2017 – 2021	National, rural and peri-urban settlements	Electricity industry and development sector
5	Assessment of policy implications	Long term outlook	National, rural and peri-urban settlements	Energy industry and development sector

1.9 Data considerations

The methodological framework developed for this research drew upon several disciplines. The data requirements were therefore diverse and reflected the multi-disciplined nature of the framework. Data requirements comprised of data on current energy demand, energy use, consumption patterns, household income, technical viability, economic viability, environmental and social parameters.

1.9.1 Data sources

The study made use of secondary data from trusted government and academic websites and databases. Quantitative data was collected from the industry and infrastructure projects databases of local, provincial and national departments of the government of South Africa.

Primary data for ranking preferences were collected through interviews and virtual engagements with members of a technical panel established for the study. The panel was made up of academics, key opinion formers, industry subject-matter experts and senior

government officials involved in rural energy infrastructure development for subjective opinion data as preferences. The three defined stakeholders included the following:

- Rural energy project experts who ensure that projects are well-engineered and technically feasible;
- Elected or appointed officials responsible for making the final decision regarding the rural energy infrastructure planning; and
- The targeted beneficiaries'/infrastructure users.

The key variables utilised in the multi-objective optimisation framework were drawn from the project's databases and comprised of a comprehensive set of factors representing financial, technical, environmental, socio-economic and political considerations. The data and other information presented were instrumental in the development of GP and MAVT models.

1.9.2 Data analysis

The data analysis process involved the use of multi-objective optimisation software packages. For the goal programming (GP) component of the framework, the problem was solved using Microsoft Excel with the Open Solver add-in (Mason, 2012). The MAVT component was solved using the Visual Interactive Sensitivity Analysis (V.I.S.A) groupware, version 8.1 for Windows (Belton, 1990). The rest of the data were analysed using Microsoft Excel, with the results presented in the form of Tables and Charts.

1.10 Study limitations

The framework developed was limited to rural and informal urban area energy planning, yet the energy access problem is much broader. Isolated rural and informal urban areas were selected because the energy access problems are more prevalent and pronounced in these areas. A study that proposes a national energy planning framework would be more applicable. This was, however, found to be complex, requiring a significant amount of time and financial resources.

Furthermore, energy planning at the national level in South Africa is mostly legislated, leaving no room for alternative methodologies. Also, the framework developed was only illustrated for low-income energy access planning in South African rural and informal areas. However, the main principles highlighted and explored in this study are most likely valid for many developing and under-developed countries with low levels of electrification rates.

Lastly, an essential limitation of the study was the difficulty in securing appointments with senior decision-makers in government to participate in the strategic dialogues. As a result, virtual face to face and strategic discussions with a panel of experts representing decision-makers were conducted. Further efforts to organise meetings during the first quarter of 2020 were hampered by the emergence of the novel coronavirus pandemic of 2019 (Covid-19). Nonetheless, insights obtained from strategic dialogues conducted through face to face and virtual conferencing platforms are considered adequate and exhaustive to shape the form of the framework developed and addressed the research questions and objectives.

1.11 Organisation of the thesis

This study report comprises a total of eight chapters. Table 3 presents a summary of the main contents of the thesis and the corresponding function and the tasks.

Table 3: Contents of the thesis

Chapters	Function and tasks
Chapter 1: Introduction.	Introduction and background of the thesis.
Chapter 2: Status quo: low-income households' access to energy.	An investigation of the current low-income household energy supply situation in the country. Chapter 2 aims to unpack the evolution of rural energy infrastructure development in the country. The section also identifies the unserved areas to reveal the possible shortcomings in the current approach to ensuring access to energy in the country. This chapter sets the scene and is a precursor to Chapter 5, which expands on the problem statement, and this is where the framework developed was applied to the problem and analysed.
Chapter 3: Multi-criteria decision analysis theory.	An examination of theoretical MCDA and decision theory literature. Chapter 3 highlights some of the essential theoretical foundations regarding decision theories and how these theories relate to strategic decision-making in the areas of energy planning and strategic public policy formulation.
Chapter 4: A review of empirical studies.	Survey of MCDA techniques used within the energy planning industry and fields of decision analysis. Evaluate techniques and conclude which aspects are relevant concerning the present study and framework developed. The chapter discusses the salient features of existing studies on the application of MCDA to strategic rural energy planning. This chapter identifies significant gaps and limitations in existing studies and assists in the development of a more robust MCDA framework for strategic rural energy planning

Chapters	Function and tasks
Chapter 5: A framework for multi-criteria decision analysis in rural energy supply planning.	Development of a transparent framework for multi-criteria decision-making based on findings and conclusions arising from Chapter 1 to Chapter 4 and the strategic engagements with a panel of industry experts. The section deals with the central issue of the research project; the task of constructing a multi-objective and multi-criteria decision-support framework for planning low-income household energy supply interventions.
Chapter 6: Selection of a portfolio of energy supply options for low-income households in South Africa using the GP technique.	Application and validation and refinement of the GP framework developed based on fieldwork conducted with a panel of experts.
Chapter 7: Evaluation and selection of strategies using the value function technique.	Application and validation and refinement of the value function framework developed based on fieldwork conducted with a panel of experts.
Chapter 8: Research findings, conclusions and recommendations.	Research findings, conclusion and recommendations.

1.12 Chapter conclusion

The chapter provided the basis and foundation for the research. The section presented research objectives, including the main goal, which was to develop and apply a decision-support framework for evaluating portfolios of energy supply technologies and development plans that will result in access to sustainable energy among low-income households in isolated rural areas as enunciated in the global SDGs and national strategic plans. The chapter also presented the research framework, scope and significance of the study. The next section explores the theoretical and empirical literature on the status of the energy access situation among low-income households in South Africa.

CHAPTER 2

STATUS QUO: ACCESS TO ENERGY BY LOW-INCOME HOUSEHOLDS

2.0 Chapter introduction

This chapter presents a review of the development and status of rural household energy supply in South Africa. The section provides the context of the research area. The focus is on location characteristics and the rural energy infrastructure in the country. The chapter explores the shortcomings in the current approach to ensuring access to energy. This chapter sets the scene and is a precursor to Chapter 8, which expands on the problem statement, and this is where an MCDA technique was applied to the problem and analysed.

2.1 South African rural areas

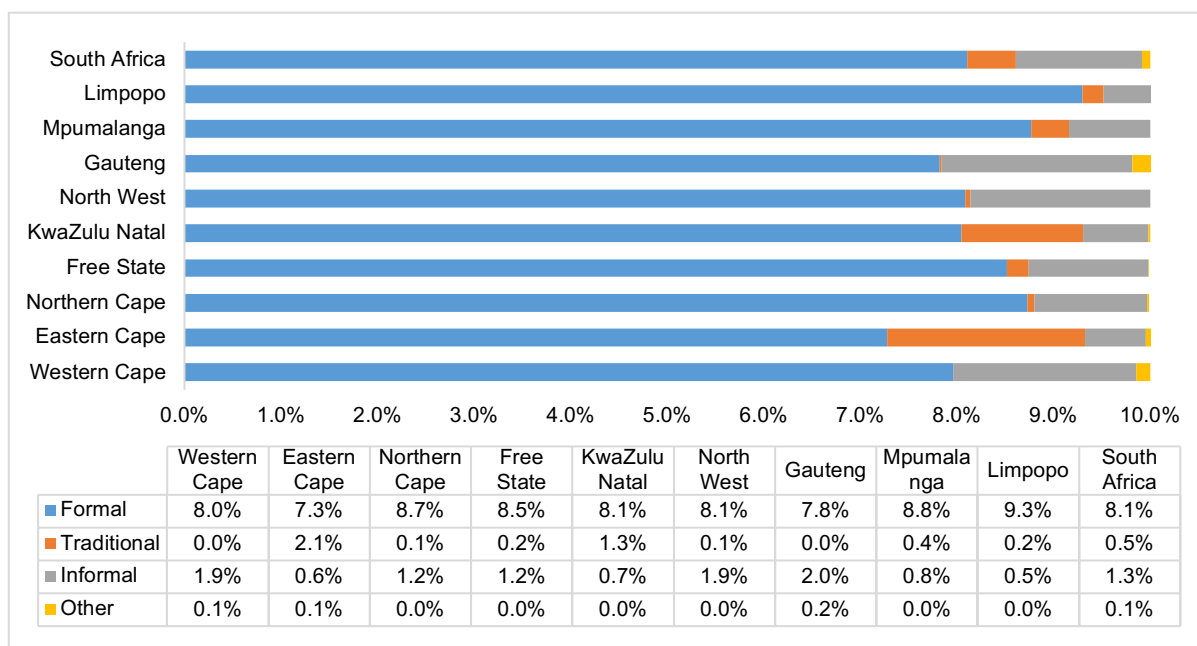
The Department of Rural Development and Land Reform (DRDLR) defines rural areas as sparsely populated settlements where households depend on farming and natural resources (Gwanya, 2010). These areas comprise mainly small towns, hamlets and villages. The DRDLR further divides rural areas into three broad settlement types. These settlements include commercial farming areas, tribal homelands and informal settlements. In the communal areas, the community owns the land through chieftaincies. Some rural regions are geographically isolated and sparsely populated (Gwanya, 2010). The dispersive nature of these settlements further complicates the economics of providing grid electricity to these areas (Howells et al., 2005; Winkler, 2006). It is also costly to build transmission and distribution lines connecting dispersed households (Winkler, 2006). According to Lahimer et al. (2012), “rural electrification is a complicated issue because of user affordability, rural inaccessibility and remoteness, low population densities and dispersed households, low project profitability, fiscal constraints, scarcity of energy resources, high population growth, lack of professionalism and over-dependence on subsidies”. The study scope excludes commercial farming areas.

Temporary dwelling structures characterise informal settlements in urban areas. Energy consumption patterns in these areas mirror those in rural areas Nabudere (2006). Nabudere (2006) argued that the term “rural area” should not be associated with physical geographical localities as doing so shrouds the understanding of poverty and inequality in the country. Nabudere (2006) posited that the gulf between the skyscraper economy and the shanty economy in South Africa matches the gap between rural and informal urban areas in the country. This narrative reinforces the argument that when designing intervention energy

access programmes to benefit poor rural households, these initiatives should also include solutions for underprivileged homes located in informal urban areas.

As shown in Figure 2, about 30 million people live in rural areas (Stats SA, 2019). Approximately 80 per cent of the South African population live in formal dwellings. About 13 per cent of people live in informal and low-income settlements. The remaining five per cent reside in traditional homes (Stats SA, 2019). The Limpopo, Mpumalanga and Northern Cape provinces account for the highest concentration of formal dwellings. Informal urban settlements are concentrated in Gauteng, the Western Cape and North-West regions. Approximately 19 per cent of homes in these provinces are considered informal. Traditional dwellings, about 20.5 per cent, are concentrated in the Eastern Cape province (Stats SA, 2019).

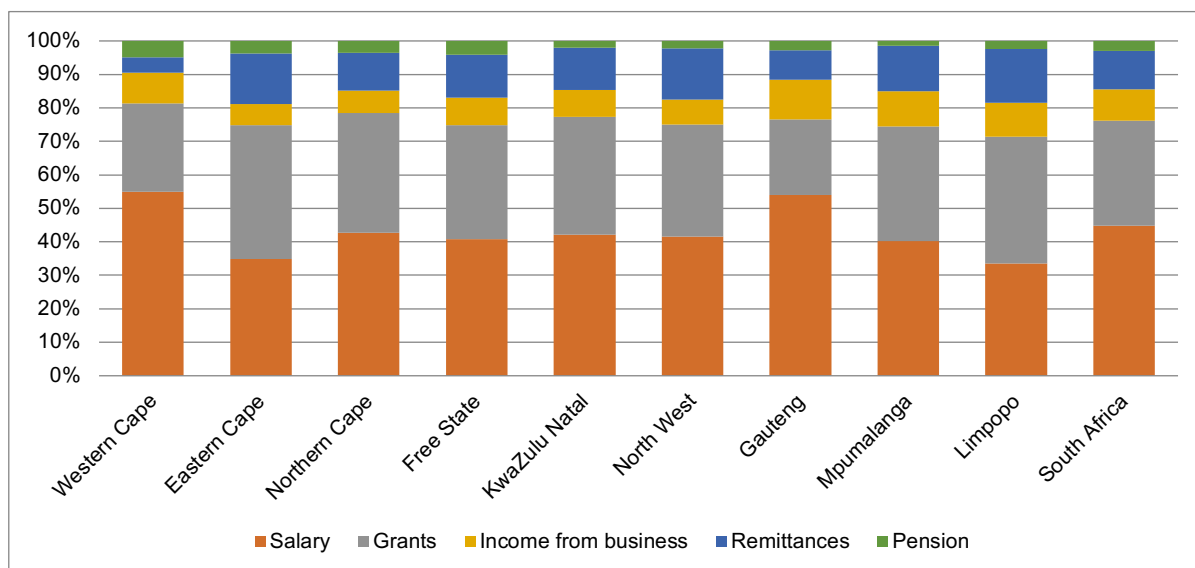
Figure 2: Dwelling type by province, 2018



Source: General Household Survey (2019)

Figure 3 shows that owing to high unemployment levels, low-income families rely on social grants and remittances (Stats SA, 2019). For example, except for the Gauteng and the Western Cape provinces, over 50 per cent of families in South Africa rely on social grants. Except the Western Cape provinces; remittances are also a primary source of income across the country, accounting for approximately 17 per cent of household income (Stats SA, 2019).

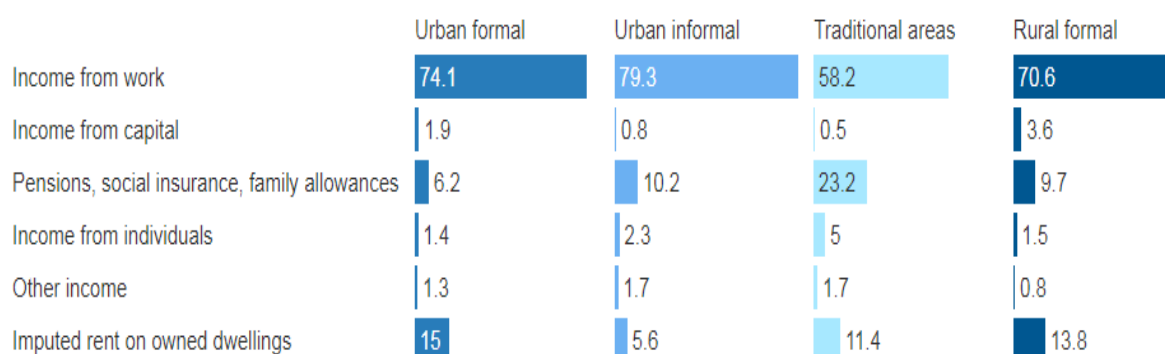
Figure 3: Main source of income by province, 2018



Source: Stats SA (2019)

In 2017, Mathebula et al. estimated household income diversification in settlement types of the poorest provinces using data obtained from the 2011 Income and Expenditure Survey, Stats SA and Wave 3 data from the National Income Dynamic Study (Figure 4). Their findings confirm the 2018 GHS statistics. Mathebula et al. (2017) found that the primary source of income for most households in rural and informal settlements are social grants, remittances and subsistence farming. This status quo has not changed, as revealed in the latest GHS survey results.

Figure 4: Annual household income by settlement type



Source: Mathebula et al., 2017

According to Stats SA data (Stats SA, 2016), as shown in Table 4, the yearly household income for informal urban areas was estimated at R58 488 (real terms) while for traditional

areas the figure was estimated at R56 333 (real terms). This presents further evidence of similarities of life between informal urban areas and isolated rural areas.

Table 4: Income by dwelling type, 2016

Source of Income	Urban formal	%	Urban informal	%	Traditional areas	%	Rural formal	%	Total	%
Income from work	140 453	74.1	46 384	79.3	32 812	58.2	59 928	70.6	100 246	72.4
Income from capital	3 665	1.9	480	0.8	261	0.5	3 026	3.6	2 451	1.8
Pensions, social insurance, family allowances	11 732	6.2	5 991	10.2	13 090	23.2	8 200	9.7	11 738	8.5
Income from individuals	2 708	1.4	1 343	2.3	2 803	5.0	1 304	1.5	2 542	1.8
Other income	2 511	1.3	1 022	1.7	937	1.7	698	0.8	1 886	1.4
Imputed rent on owned dwellings	28 499	15.0	3 268	5.6	6 430	11.4	11 741	13.8	19 665	14.2
Total	189 568	100	58 488	100	56 333	100	84 897	100	138 528	100

Source: Living Conditions of Households in South Africa 2014/2015 Survey (Stats SA, 2016)

A report by Oxfam South Africa has shown that more people in South Africa are becoming impoverished. The number of people living below the food poverty datum line was estimated at 13.8 million in 2015 people (Lawson et al., 2019). This number represents 25 per cent of the population. In 2015, the food poverty datum line was estimated at R441 per person a month in real terms. (*Ibid*).

Chitiga-Mabugu et al. (2014) found high levels of poverty among families living in rural areas and informal urban areas located in the Limpopo, Eastern Cape and KwaZulu Natal provinces. In these areas, soil erosion, soil desertification, agricultural water resources shortage and lowering of the water table characterise these areas because of inferior farming methods (*Ibid*). Agricultural activities are limited to subsistence livestock and crop farming and very few households generate income from agricultural activities (Chitiga-Mabugu et al., 2014).

The findings by Chitiga-Mabugu et al. (2014) are consistent with the 2018 GHS statistics (Stats SA, 2019), which showed similar patterns of high poverty levels in the Eastern Cape and Limpopo provinces. The 2018 GHS statistics also revealed that the most vulnerable persons to poverty in South Africa are children below the age of 17, women, black Africans, people with little or no formal education and families living in rural and informal urban areas.

2.2 Energy consumption in low-income households

The study used data obtained from the 2018 GHS and the 2016 Community Survey for South Africa to analyse rural household consumption levels and patterns between 1996 and 2016. According to Adkins et al. (2012), the principal energy uses by rural households in Sub-Saharan Africa fall under three main categories, namely:

1. Cooking and heating;
2. Lighting and power for charging electronic devices charging (e.g., mobile phones, radios and televisions); and
3. Agro-processing and water pumping.

Adkins et al. (2012) also established a strong reliance on solid fuels (firewood, cow dung) in about 3000 rural households across Sub-Saharan Africa. Therefore, it can be concluded that the majority of rural households use energy mainly for cooking and heating, lighting and running small electrical appliances..

Before 1994, it was estimated that over two-thirds of the South African population did not have access to electricity (Winkler et al., 2006; Bekker et al., 2008). Between 1994 and 2016, Eskom connected an estimated 6.6 million households to the grid to address the anomaly.. This was achieved under the auspices of several interventions, such as the National Electrification Programme (1994 to 1999) and the INEP (DMRE, 2016). It was expected that electrification would help households transition from using firewood, candles and batteries to using electricity (Winkler et al., 2006).

In 2003, the government introduced the EBSST, whose aim was to provide free basic electricity for low-income households up to 50-kilowatt hours (kWh) per month. The 50 kWh per month was considered sufficient. Another intervention, the SHS programme, was introduced to ensure access to off-grid electricity for 350 000 families living in isolated areas who could not be easily and economically connected to the central grid. The FBAE programme was launched in 2005 to augment and address some flaws of the EBSST and the SHS initiative.

Approximately 85 per cent of households in South Africa have access to grid electricity (Stats SA, 2019). Whereas electrification rates are high in informal urban areas, electrification in rural provinces is in the 20-34 per cent connected threshold. An estimated 3.3 million households in rural areas and informal urban settlements are not connected to the central grid (DMRE,

2016). The primary source of energy among these families are traditional solid fuels and kerosene (Shackleton et al., 2006; 2007).

In 2017, Hughes et al. (2017) identified unelectrified areas in South Africa using the census data and descriptors for the unelectrified regions such as distance to the medium voltage stations, presence of schools, clinics, mean household income levels and the like at the Stats SA's Small Area Layer (SAL) level. The study revealed that most un-electrified SALs are located in the Eastern Cape, Kwa-Zulu Natal and Limpopo provinces. Still, there are pockets of un-electrified regions in all provinces. The present study aimed to address the energy access problem for families living in the areas identified by Hughes et al. (2017).

Table 5 shows the number of SALs that are un-electrified in each province. The table also presents the un-electrified population estimate and the number of SALs with no electricity (Hughes et al. 2017). The study revealed that there are approximately 3 970 rural un-electrified areas in South Africa, accounting for a total household population of 291 252 in 2017.

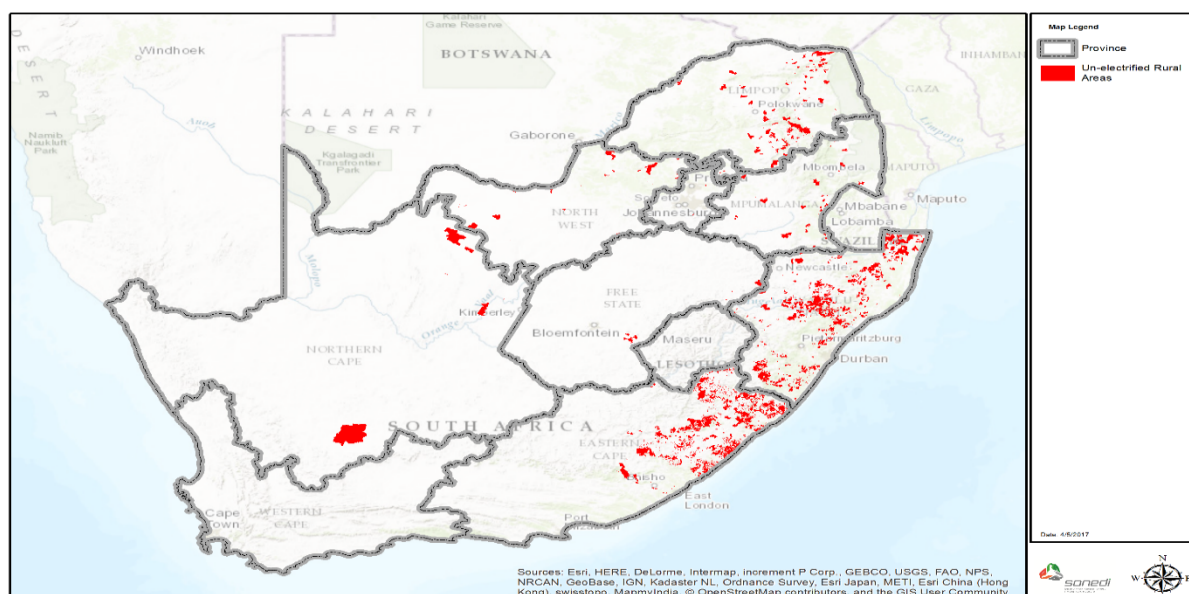
Table 5: Un-electrified rural areas

Specific Objective	Number of populated SALs	Number of Households	SALs with no Electricity
Eastern Cape	2 571	166 305	2 072
Free State	10	597	58
Gauteng	6	936	17
KwaZulu-Natal	1 039	96 885	360
Limpopo	208	11 349	698
Mpumalanga	51	3 342	142
North-West	64	10 155	238
Northern Cape	21	1 683	49
Western Cape			38
Total	3 970	291 252	3 672

Source: Hughes et al. (2017)

Figure 5 presents the areas where most of the unelectrified households are located in the country.

Figure 5: Un-electrified rural areas in 2017



Source: Hughes et al. (2017)

Lack of coordination and resources, the absence of clearly defined strategies and multiple approaches to the energy access problem hinder the success of energy access efforts in South Africa. Perspectives on the best energy access approach differ across stakeholders involved in the energy access programmes in the country. For political expediency, policymakers generally favour electrification.

2.3 Energy for cooking in low-income households

Cooking accounts for a significant share of energy consumption in most low-income households. Modi et al. (2005) estimated the cooking energy demand at one gigajoule per year per capita “into the pot, within a factor of two”. This energy is mainly sourced from traditional solid fuels (Griffin et al., 1992). In informal settlements, kerosene is the primary source of energy for cooking. In these areas, kerosene meets as high as 22 per cent of energy needs for cooking across the country (Stats SA, 2019).

On the surface, statistics show high grid electricity usage for cooking, whereas a detailed analysis by dwelling type indicates that the usage of firewood and kerosene for cooking in most traditional rural and informal dwellings remained significantly high. In essence, less than half of households use electricity for cooking. Electric stoves and electricity bills are generally beyond the reach of most families in these areas (Howells et al., 2005). Shackleton et al. (2007) estimated the annual demand for firewood in low-income households to be between 1 200 - 1 800kg per household, circa 320 to 360 kg per person per year.

Electricity expenditure is positively correlated with total household and per capita income (Shackleton et al., 2006). The same direct relationship and greater reliance on firewood for meeting energy needs by low-income families were observed across Sub-Saharan Africa (Adkins et al., 2012); Zimbabwe (Vermeulen et al., 2000), Southern and Eastern Africa (Gielink, 1991; Davis, 1998; Matsika et al., 2013), Rwanda (Ndayambaje, 2013), Ireland (Healy and Clinch, 2001), West Africa (Johnson and Bryden, 2012) and in Mozambique (Cuvilas et al., 2010).

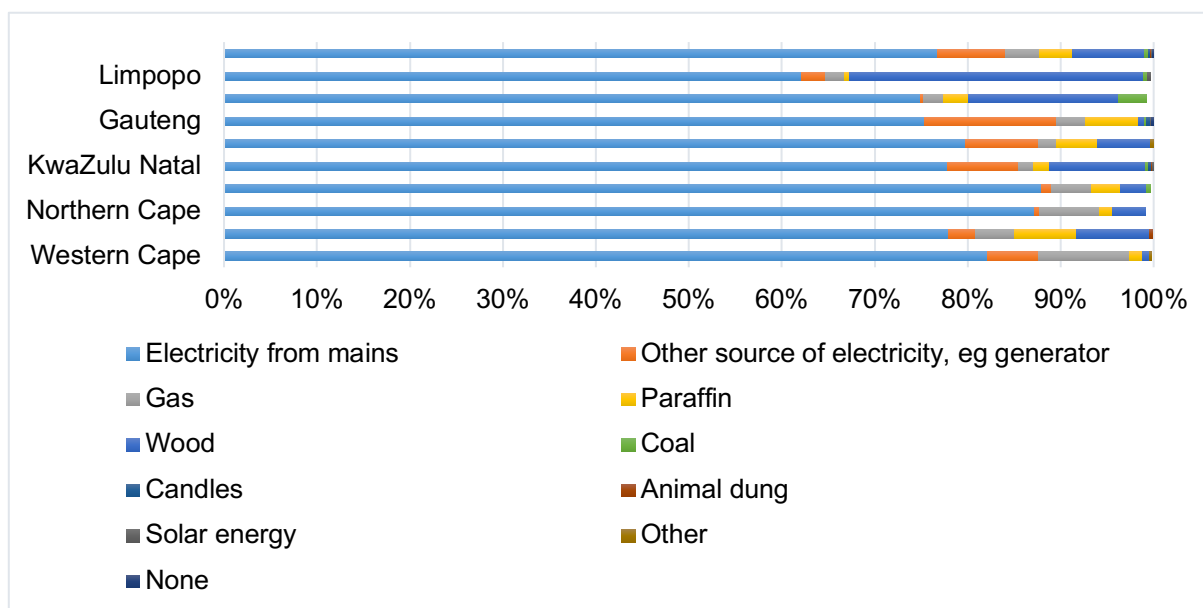
Energy sources for cooking across the country

Further analysis of energy sources for cooking across the country shows that the numbers vary by province and type of dwelling of households (Stats SA, 2019). The use of grid electricity for cooking is higher in the Northern Cape (circa 86 per cent), followed by the Free State (84 per cent) and the Western Cape (81 per cent).

The use of grid electricity is lower in the more rural provinces of Limpopo, North-West, Eastern Cape and Mpumalanga. For instance, grid electricity used for cooking in the Limpopo province accounts for approximately 60 per cent. In comparison, it is 69 per cent in Mpumalanga, the Eastern Cape, and the North-West Province.

Again, data analysis at the provincial level fails to provide a clearer picture. Figure 65 shows the distribution of households by energy source by province for cooking according to data extracted from the 2018 GHS published by Stats SA.

Figure 6: Distribution of households by energy source for cooking by province, 2018



Source: Stats SA (2019)

The use of kerosene in the country is most common in the Eastern Cape, where approximately seven per cent of households and least common in Limpopo, the Western Cape and the Northern Cape, roughly one per cent. The low use of electricity for cooking in Limpopo and Mpumalanga provinces is primarily attributed to the easy accessibility and affordability of alternative fuel sources such as firewood. In the Limpopo province, almost 32 per cent of households use firewood for cooking (Stats SA, 2019).

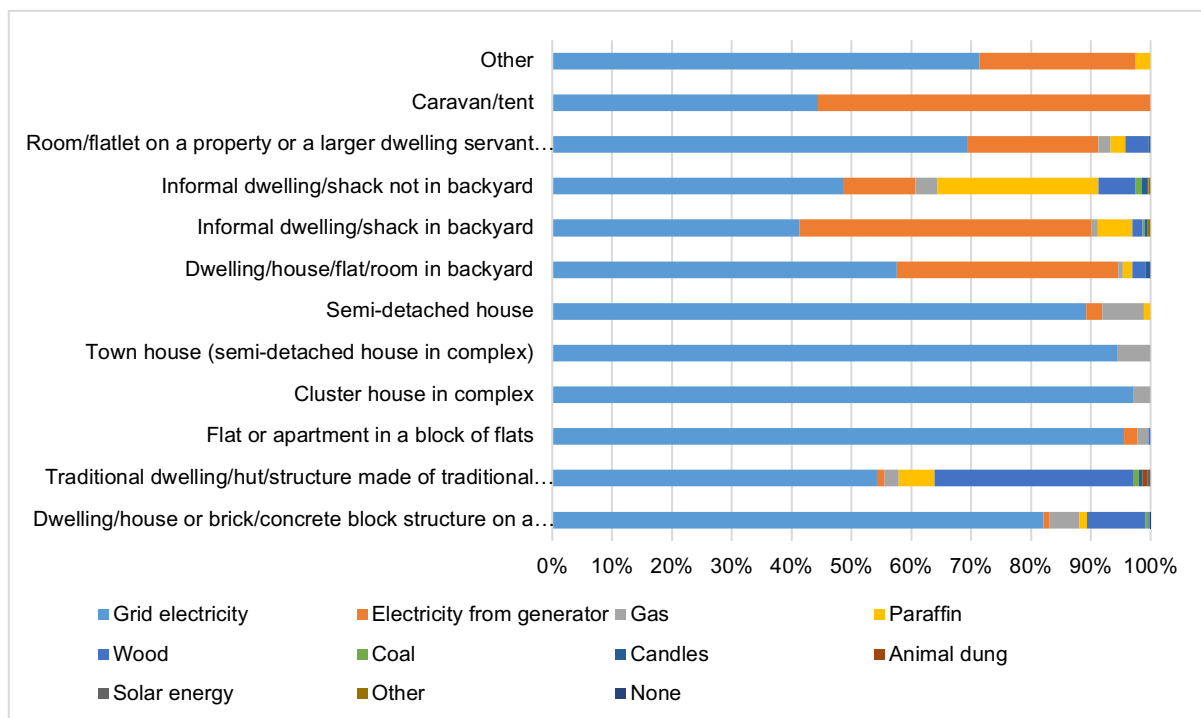
Similarly, in Mpumalanga, firewood accounts for approximately 16 per cent of household energy used for cooking. The figure is ten and eight per cent in KwaZulu-Natal and Eastern Cape provinces, respectively. The use of firewood is lowest (less than one per cent) in the Western Cape and the Gauteng provinces. The use of liquefied petroleum gas (LPG) is most prevalent in the Western Cape, Northern Cape and the Free State provinces. According to Stats SA, the penetration rate remains low, less than eight per cent per year. (Stats SA, 2019).

Primary source of energy for cooking by dwelling type

The use of firewood and kerosene for cooking in traditional rural and informal urban dwellings is relatively high, according to Stats SA (Stats SA, 2019). In these homes, closer scrutiny of the statistics reveals that over 40 per cent of households in traditional dwellings relies on conventional biomass energy, mainly firewood and cow dung, for cooking. This figure accounts for over one million homes (Stats SA, 2019).

In the informal urban dwellings, kerosene for cooking accounts for over 30 per cent and approximately seven per cent in traditional houses (Stats SA, 2019). Many electrified and non-electrified low-income households use kerosene because of its affordability, portability and availability. The 2018 GHS statistics confirm the argument that energy consumption levels in the informal urban areas mirror rural energy consumption patterns as claimed by Nabudere (2006) over a decade earlier. Figure 7 presents a summary of household energy consumption patterns for cooking.

Figure 7: Source of energy for cooking by dwelling type, 2018



Source: Stats SA (2019)

The 2018 Stats SA statistical results presented in Figure 7 are divergent from policymakers' expectations. These results corroborate empirical investigation findings which show that the consumption of electricity for cooking has remained low among low-income families even with the introduction of electricity (Davis, 1998; Thom, 2000; Prasad and Ranninger, 2003; Madubansi and Shackleton, 2006; Chirwa et al., 2010; Matsika et al. 2013). Prasad and Ranninger (2003) reported that 56 per cent of electrified rural homes consumed less than 50 kWh per month in 2000 against an anticipated consumption level of 350 kWh per month.

2.4 Heating primary sources of energy

Energy for heating takes two forms, water and space heating. Space heating constitutes the bulk of energy consumption for heating and is highest during winter. Historically, firewood, cow dung and kerosene contributed the most considerable portion of energy for heating by rural households. In informal urban settlements, kerosene and braziers (*mbawula*) are the most common energy source for heating. The uptake of solar geysers is slowly increasing on the back of strong government support in the past decade and the falling solar technology prices.

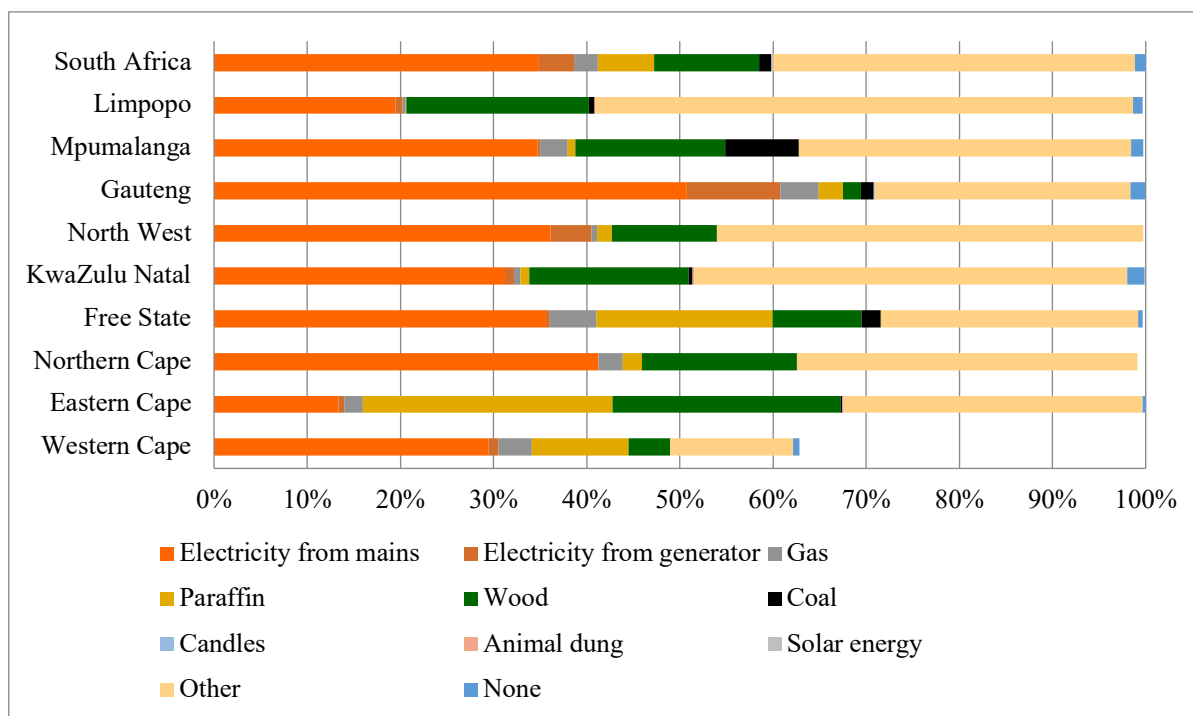
As shown in Figure 8, across the country, electricity for heating accounts for approximately 34 per cent, followed by firewood, which accounts for 10 per cent. Interestingly, roughly 42 per cent of households do not use any form of energy for heating. This phenomenon is mainly because South Africa is generally warmer throughout the year and cold only in winter. Even the winters are not as severe.

Household energy sources for heating across the country vary by province and type of dwelling of households (Stats SA, 2019). The use of grid-connected electricity for heating is highest in the Gauteng Province (50 per cent), followed by the Northern Cape (43 per cent) and the Mpumalanga Province (37 per cent). However, the use of electricity for heating is slowly being overtaken by LPG. LPG is cheaper and more reliable than power.

The use of electricity connected to the mains is lowest in Limpopo, Western Cape, Eastern Cape and KwaZulu Natal and the North-West Provinces. For instance, grid electricity for heating in the Eastern Cape Province accounts for a meagre 13 per cent. In comparison, it is 27 per cent in Limpopo, KwaZulu Natal, the Western Cape and the North-West provinces.

Once more, data analysis at the provincial level does not provide an accurate picture of the household consumption patterns, as shall be seen later in the discussion. Figure 8 summarises of the provincial distribution of energy sources for heating according to the 2018 GHS data (Stats SA, 2019).

Figure 8: Distribution of energy source for heating by province, 2018



Source: Stats SA (2019)

In Eastern Cape and the Free State province, approximately 19 per cent of families rely on kerosene for meeting heating needs, and 10 per cent of households in the Western Cape make use of kerosene for heating. The high consumption of kerosene in the Eastern Cape, Western Cape and Free State provinces is attributed to the affordability of kerosene and the government's essential electricity augmentation interventions.

Data gleaned from the 2018 GHS data also showed high levels of firewood usage in the so-called rural provinces of South Africa, namely, KwaZulu Natal, Limpopo, Mpumalanga and the Northern Cape (Stats SA, 2019). In these provinces, firewood accounts for approximately 19 per cent of energy for heating (Stats SA, 2019). Again, the low use of electricity for heating in Limpopo and Mpumalanga provinces is attributed to firewood's easy availability and affordability. The use of fuelwood for heating is prevalent in Limpopo and the Eastern Cape Provinces, with more than 21 per cent of households estimated to be using firewood for heating (Stats SA, 2019).

Similarly, in Mpumalanga, firewood accounts for approximately 16 per cent of household energy used for heating and 17 per cent in the Northern Cape province. The use of firewood for heating is not very common in the Gauteng, the Western Cape and the North-West

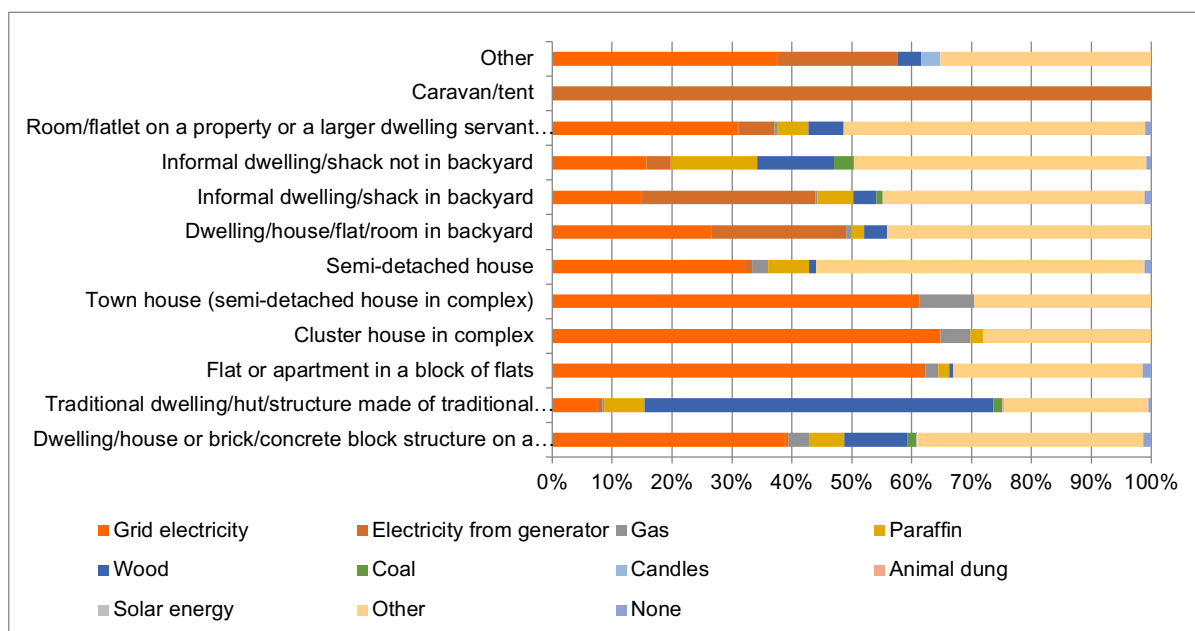
provinces. In these provinces, firewood accounts for less than 10 per cent of the heating energy mix. The low reliance on firewood in these provinces is attributed to the cost of firewood. The use of LPG for heating is widespread in Western Cape, Gauteng and the Free State provinces.

Primary source of energy and dwelling type

Energy consumption for heating differs considerably depending on the type of dwelling. Grid electricity consumption is high in homes located in areas such as town and cluster houses, flats and caravan/tents (Stats SA, 2019). In these dwellings, grid electricity accounts for over 63 per cent of the energy used for heating. In contrast, grid electricity accounts for approximately eight per cent of heating energy requirements in traditional dwellings and roughly 16 per cent in informal homes.

The use of firewood for heating is high in traditional dwellings accounting for over 58 per cent of energy requirements for heating. In informal urban dwellings, over 13 per cent of households rely on firewood for heating. Over nine per cent of households in traditional houses and informal dwellings rely on kerosene for heating (Stats SA, 2019). The high use of kerosene in informal dwellings is attributed its affordability. Figure 9 presents a summary of household energy consumption patterns for meeting heating requirements.

Figure 9: Primary source of energy for heating and dwelling type, 2018



Source: Stats SA (2019)

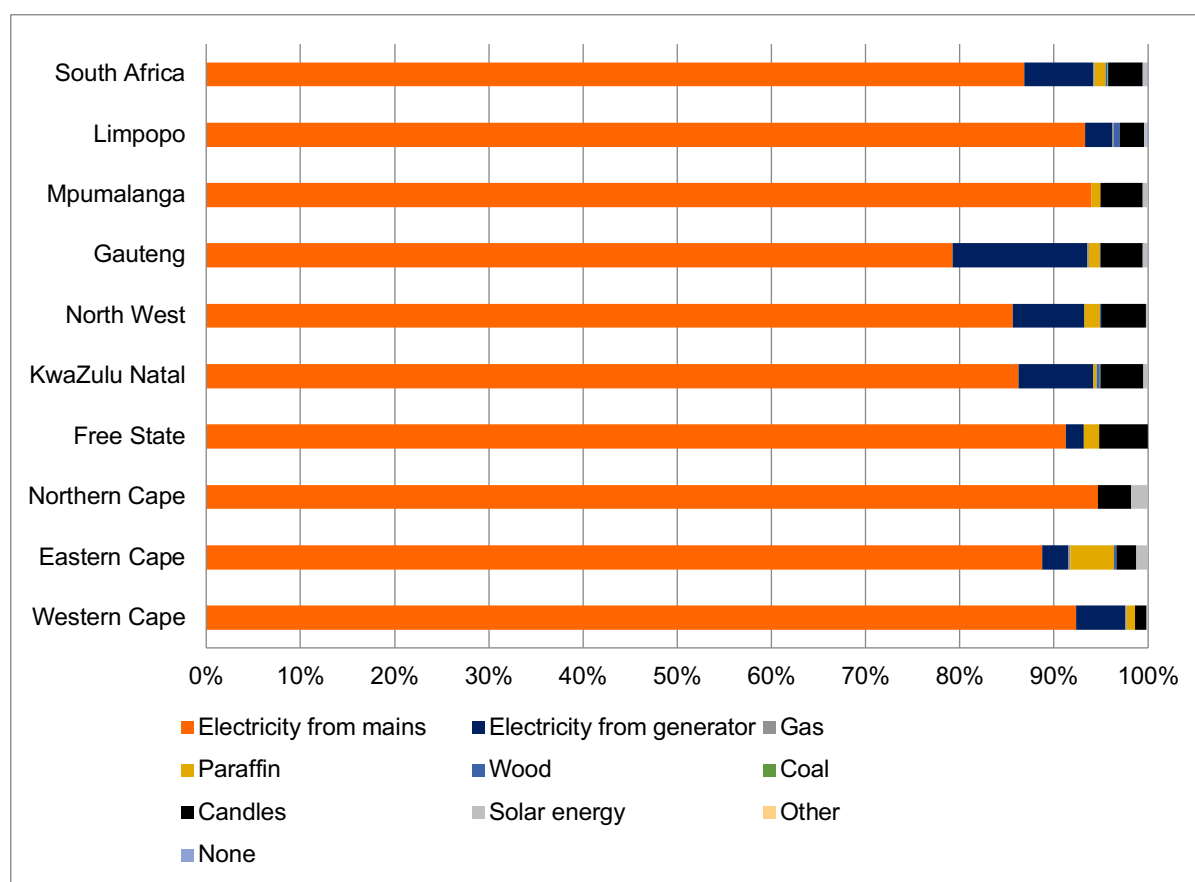
It is clear from the discussion thus far that central grid electricity consumption for heating purposes has evolved. It is projected that the use of firewood for heating will remain high in traditional and informal dwellings (Shackleton et al., 2007). Based on observed historic trends, the use of kerosene is expected to decrease over time. The emergence of solar geysers supported by government incentives and the rise of LPG as feasible alternatives to electricity and firewood for heating is expected to significantly alter the energy industry dynamics.

2.5 Sources of energy for lighting

Energy requirements for lighting purposes are generally low. The emergence of energy-efficient light bulb technologies such as the light-emitting diode is making the use of electricity for lighting purposes affordable for any household across the country. According to the Stats SA (2019) statistics, over 87 per cent of households in South Africa uses grid electricity for lighting purposes. This trend is in stark contrast with heating and cooking trends. Among informal settlements and rural homes, kerosene and candles remain significant energy sources for meeting lighting requirements. In these households, kerosene and candles contributed as high as 5 per cent of energy for lighting across the country as of 2018.

The use of kerosene for lighting purposes is high in the Northern Cape, Free State, North-West, Eastern Cape and Gauteng provinces. The high use of kerosene in these provinces mirrors the energy for heating consumption patterns in the provinces discussed above. It was observed that the use of candlelight was high in the KwaZulu Natal and Mpumalanga provinces. Approximately five per cent of low-income households in these provinces rely on candlelight for meeting lighting needs in Limpopo, Gauteng, North-West, Free State, Northern Cape and the Eastern Cape (Stats SA, 2019). Figure 10 summarises the distribution of households' energy sources for lighting according to data extracted from the GHS published in 2019.

Figure 10: Distribution of households' energy source for lighting by province, 2018



Source: Stats SA (2019)

The high utilisation rates of electricity for lighting across the country and even in the traditional and informal settlements support policymakers' expectations. Scholars, however, argue that it is possible to meet similar energy requirements for lighting using alternative technologies such as solar photovoltaics (PV) at competitive costs (Dresselhaus, 2001; Chaurey et al., 2004; Nema et al., 2009; Deichmann et al., 2011).

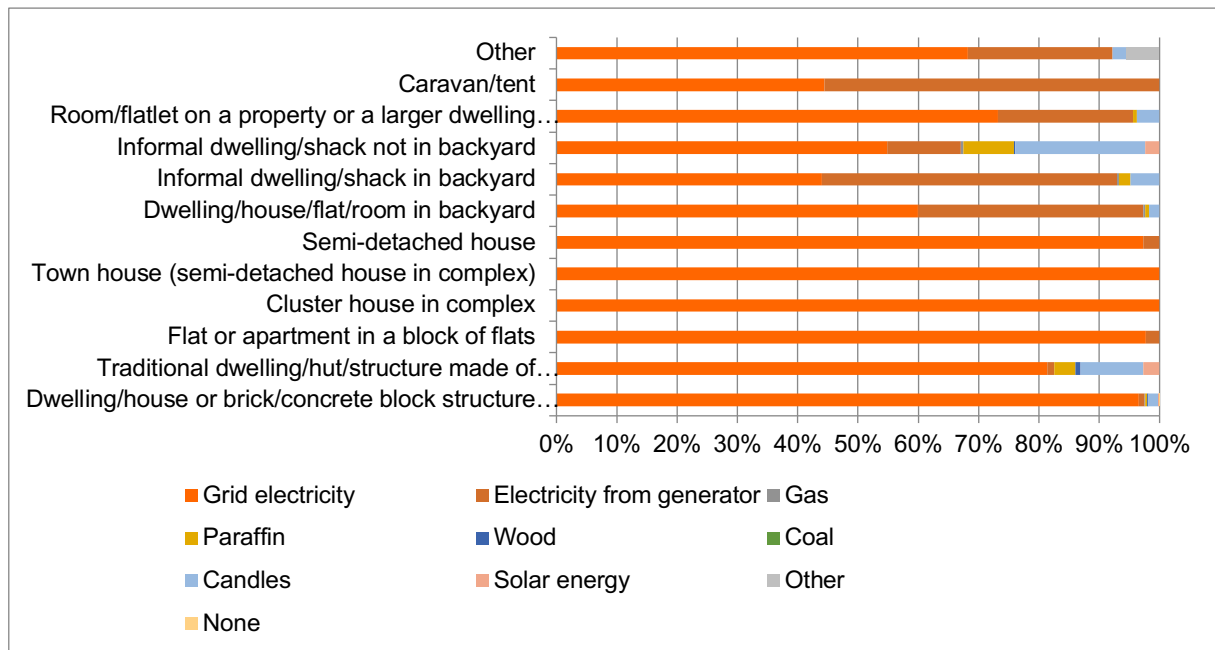
Primary source of energy for lighting by dwelling type

In most low-income households, grid electricity contributes over 95 per cent of the energy for lighting. Electricity use for lighting in backyard dwellings accounted for 60 per cent and is lowest in informal low-income areas, approximately 49 per cent according to 2018 GHS statistics. As expected, the use of candlelight is high among the informal low-income areas, approximately 21 per cent and 10 per cent in traditional dwellings.

A notable development over the years has been the adoption of off-grid solar PV systems among families living in traditional and informal dwellings (Nema et al., 2009; Deichmann et

al., 2011). As of 2018, according to the GHS statistics, solar PV accounted for roughly three per cent of lighting energy requirements for traditional dwellings located in rural areas. Over the years, solar PV has been deployed at a scale in the Eastern Cape and Limpopo provinces (Stats SA, 2019). Figure 11 presents a summary of the primary source of power for lighting by dwelling type.

Figure 11: Primary source of energy for lighting by dwelling type, 2018



Source: Stats SA (2019)

The Stats SA (2019) statistics validate empirical investigation conclusions, which show that in the low-income households, candles, kerosene and diesel energy continue to play a significant role in meeting low-income household lighting requirements, albeit an increased utilisation of grid electricity (Chirwa et al., 2010).

2.6 Service delivery in low-income areas

Many municipalities have been battling to ensure efficient and quality service delivery leading to protests. The main areas of concern are water and sanitation and energy provision. The challenges faced by the municipalities in the field of energy infrastructure development are attributed to the disjuncture between the national government department and the sub-national authorities. In energy planning, all energy policies in South Africa are formulated at the national level but are implemented at the local municipality level.

The role of the sub-national governments is to implement the provisioning of municipal services, including free essential services. While Eskom provides electricity, the funding of free basic electricity is channelled by municipalities to Eskom to pay for the free electricity that would have been provided to eligible indigent households. The National Treasury, through the equitable share grant and other grant systems, provides the funding. Several challenges exist in most small and rural municipalities due to poor financial resource management, a lack of skills and corruption. Service delivery has been compromised by poor governance.

The Municipal Systems Act (Act 32 of 2000) mandates that all local government authorities develop and adopt Integrated Development Plans (IDPs). The IDP serves as a planning and budgeting tool for municipalities. The lack of skills in rural municipalities hampers the country's effective design, implementation, monitoring, and evaluation of IDPs. The result has been generally poor service delivery manifested through service delivery demonstrations and illegal electrical connections (Seleka, 2021). It has also been shown that some rural municipalities do not have specific policies for energy strategy in their IDPs (Koelble and LiPuma, 2010).

The main challenge with initiatives such as the SHS, FBE and the FBAE has been the absence of a proper definition of indigent customers. The definition of an impoverished customer fails to distinguish between affordability and willingness to pay. As a result, the association of the term indigent with low-income has resulted in the provisioning of the free 50kWh of electricity per month to households with modern electrical appliances and high electric power requirements.

Additionally, as a result, the number of households receiving free electricity is high in rural areas, yet poorer families are living in informal urban settlements. The second main challenge with the FBE and FBAE is that in most rural municipalities, FBE and FBAE funding is not included in IDPs (Koelble and LiPuma, 2010).

The Biomass Initiative, which was introduced in 1992 to improve the supply of firewood to rural households upon the realisation that biomass still played an integral role in meeting rural thermal energy requirements, was discontinued in 1996 owing mainly to a lack of support for the project from the DMRE as the department favoured grid electrification (Marquard, 2006).

According to Kimemia et al. (2014), due to poor handling and unsafe use of kerosene, an estimated 200,000 people have either been injured or have lost property due to kerosene induced fires in South Africa. The high occurrence of fires in townships, burns and deaths resulting from kerosene-related fires prompted the authorities to introduce several

interventions. The first such intervention was the kerosene safety campaigns targeting kerosene users, which commenced in 1996, led by the Paraffin Safety Association of Southern Africa (PASASA).

However, according to Matinga (2010), most rural households remained oblivious of such campaigns. Budgetary constraints and lack of human resources and formal engagement structures in rural and informal urban settlements hamstrung the PASASA campaigns. A South African Bureau of Standards (SABS) safety test of 10 prominent kerosene stove brands in 2004 revealed that over nine out of ten kerosene stoves tested did not meet the SABS standard safety requirements.

Notwithstanding a ban on non-compliant stoves effected in 2007, some rural and informal households still use the unsafe kerosene stoves. The importation of cheap Chinese made stoves such as the Panda effectively rendered the ban ineffective. Kerosene usage statistics (GHS, 2018) indicate the success of the PASASA-led initiatives as kerosene sales have decreased substantially in the past decade (GHS, 2018).

The off-grid solar electrification programme with fee-for-service concessions was launched in 1999. No work has been conducted to test the success of the project. However, DMRE statistics suggest low uptake as most rural households prefer grid electricity to off-grid for several reasons.

2.7 Discussion

The study established that approximately 95 per cent of low-income households in rural areas with access to electricity still rely on firewood as a primary source of energy for cooking (Davis, 1998; Goldemberg, 2000; Thom, 2000; Gaunt, 2005; and Madubansi and Shackleton, 2006). Thom (2000) posited in 2000 that a significant percentage of low-income households “own but rarely use electrical appliances such as hotplates, kettles, refrigerators, televisions and radios/hi-fi equipment”. Many families in rural areas continue to use battery-powered radios, candles for lighting and kerosene for cooking and heating. In other words, electricity is considered an additional energy supply option to the existing and favoured traditional fuels (Thom, 2000; Winkler, 2006).

In 2006, Madubansi and Shackleton profiled energy consumption patterns in the Bushbuckridge district following electrification. They found that despite more than ten years of electrification, the use of firewood for meeting thermal requirements such as cooking remained high (Madubansi and Shackleton, 2006; Matinga and Annegarn, 2013).

Shackleton et al. (2006, 2007) investigated the demand and marketing of firewood in low-income suburbs of Grahamstown, located in the Eastern Cape of South Africa. They concluded that households use electricity and kerosene with electricity exclusively used for lighting and kerosene for cooking in these low-income suburbs. In small towns, firewood is part of local livelihoods and the informal economy despite electrification (Shackleton et al., 2006, 2007). The use of firewood for cooking was found to be linked to cultural beliefs. In African culture, certain cultural rituals require the use of specific tree species for ceremonial sacrifices and food cooking (Matinga and Annegarn, 2013).

A comparable study conducted by Africa et al. (2008) noted that between 2005 and 2008, the use of electricity for cooking increased in some low-income households in Grahamstown East. The study, however, showed that kerosene remains a preferred source of energy for heating. The demand for firewood fell dramatically between 2005 and 2008. However, Africa et al. (2008) noted that energy transition is hampered by network capacity constraints and suggested the deployment of renewable energy to close the gap.

Earlier in 2007, Shackleton et al. had also recommended that energy planners in South Africa ensure an adequate mix of energy supply options in low-income families. A vital aspect of this study was the development of a portfolio (s) of rural energy supply options that, if implemented, will maximise synergies and minimise duplications.

While Africa et al. (2008) noted an increased use of electric power for cooking, heating, and lighting, their findings cannot be relied upon to make conclusive statements about electricity usage. For example, work by Chirwa et al. (2010) established that in two rural villages (Cata and Tshoxa) located in the Keiskammahoek, Eastern Cape, firewood accounts for 60 per cent of the energy mix for cooking, with approximately 90 per cent of households in these areas using firewood for cooking despite electrification. Cata has one of the highest levels of electrification in the Eastern Cape province, with roughly 84 per cent of households having access to electricity (Chirwa et al. (2010).

Chirwa et al. (2010) and Matinga and Annegarn (2013) also studied behavioural attributes regarding energy use during food preparation and found that given the long time to prepare such as grains, tripe, meat and beef, most households prefer firewood cooking food to electric power. At least six hours is required for cooking traditional meals such as *umqusho* (dried, stamped and chopped white corn kernels and beans) and *umkhupha* (steamed bread) in the Eastern Cape (Matinga and Annegarn, 2013). Chirwa et al. (2010) recommended the adoption of clean, energy-efficient firewood cookstoves.

Most recent empirical investigations by Matsika et al. (2013) reinforce the argument that the use of firewood for meeting thermal energy requirements remains high. Over two-thirds of electrified rural households still use firewood as the primary source of energy to meet daily household needs. LPG and kerosene energy sources are considered alternatives to firewood and electricity by most households (Matsika et al. (2013).

In rural areas, the demand for firewood is considered to be inelastic (Matsika et al., 2013). The low adoption of electricity for meeting thermal requirements was attributed to the high cost of electric power relative to the household income and the cost of electrical appliances. Many households in low-income areas cannot afford to buy electrical appliances. (Davis, 1998; Williams and Shackleton, 2002; Howells et al., 2005).

The increased use of firewood presents challenges given the continued and unsustainable cutting down of trees. Fuelwood is becoming scarce. The continued reliance on firewood, if unabated, will result in deforestation. Woodlands near low-income settlements are considered most vulnerable, as argued earlier by Banks et al. (1996) and Carte Blanche (Carte Blanche (2020a, 2020b). These findings suggest that energy access interventions should be based on a combination of different energy sources. This argument provided the motivation and justification for the present study, whose findings and recommendations mirror what most scholars have argued over the years.

2.8 Chapter conclusion

This chapter provided a description of the research location, its main features and the energy supply situation in the country among low-income households. This chapter provided an analysis of the evolution of South African rural energy access issues. The section identified existing energy supply options and an understanding of the historical trends that have shaped the energy policy and development agenda for low-income households in South Africa.

It is observed that comprehensive energy interventions based on a combination of different energy fuels are the most suitable for addressing the energy access problem and the achievement of the broader socio-economic goals. In many low-income households connected to the central grid, power is used to run electrical appliances that require very little power such as radios, mobile phones and television sets (Lhendup, 2008). Traditional sources of energy, such as firewood, are used for cooking and heating, further entrenching poverty.

Chapter findings suggest that there is a need for an approach that considers the aspirations of different actors to a problem as opposed to a one size fits all approach. Therefore, the next

chapter explores the detailed theoretical underpinnings and foundations of MCDA thinking, which forms the basis for extended empirical applications of MCDA techniques to rural energy planning.

CHAPTER 3

MULTI-CRITERIA DECISION ANALYSIS THEORY

3.0 Chapter introduction

The Chapter examines the theoretical foundations of MCDA techniques. It highlights some of the essential aspects of decision theories on how these theories relate to strategic decision-making in energy planning in the public sector. The Chapter concludes with a comprehensive discussion on the theoretical foundations of the GP technique, the MAVT technique and the justification for their use in the procedure developed for the present study.

3.1 Multi-criteria decision analysis

Multicriteria decision analysis (MCDA), sometimes known as multicriteria decision making (MCDM), is a technique for making decisions with several competing criteria. (Belton and Stewart, 2010; Köksalan et al, 2011). MCDA techniques gained popularity in the last half-century (Huang et al., 2011). The goal in MCDA is to formalise the inclusion of quantitative, qualitative, monetary and non-monetary factors into decision analysis. MCDA is described in numerous textbooks. It comprises multiple decision evaluation techniques employed in situations where judgment depends on more than one criterion and diverse stakeholders with conflicting objectives. (French, 1989; von Winterfeldt and Edwards, 1993; Lootsma, 1999; Belton and Stewart, 2002; Goodwin and Wright, 2009).

MCDA issues can range from those that touch our everyday lives, such as purchasing a car, to those that affect a country, region, or the world, such as the use of public funds while accounting for value for money. Despite their diversity, all MCDA problems have the following characteristics in common (Hwang and Yoon, 1981).

- *Multiple criteria*: each problem has multiple criteria, which can be objectives or attributes;
- *Conflict among criteria*: multiple criteria conflict with one another.;
- *Incommensurable unit*: the units of measurement for criteria may differ.; and
- *Design/selection*: solutions to an MCDA problem are either to design the best alternatives or to select the best one among previously specified finite alternatives.

There are two types of criteria: objectives and attributes. Therefore, the MCDA problems can be broadly classified into two categories:

- i) Multiobjective decision making (MODM); and
- ii) Multi-attribute decision analysis (MADM)

The primary distinction between MODM and MADM is that the former focuses on continuous choice spaces, generally mathematical programming with multiple objective functions, whilst the latter focuses on discrete decision spaces.

Hwang and Masud (2012) and Hwang and Yoon (1981) provide some basic solution concepts and terminologies for further discussion regarding MODM and MADM.

- *Evaluation criteria (interests)* are the standards of judgment or rules used to determine whether something is acceptable. It denotes attributes and/or aims in the MCDA literature. In this context, any MCDA problem can be either MODM or MADM, albeit MADM is more commonly utilized.
- *Objectives*: decision makers' desires are reflected in objectives, which show the direction they want to operate. As a result, an MODM challenge entails the creation of alternatives that optimize or best satisfy the decision makers' goals.
- *Goals* are desires articulated in terms of a particular state in place and time by decision-makers. On the other hand, goals provide a desired or target level to accomplish, whilst objectives provide the intended direction.
- *Attributes*: alternatives' attributes are their characteristics, qualities, or performance factors. The best alternative from a pool of pre-selected alternatives characterized in terms of their attributes is chosen in a MADM issue.

The process of developing MODM and MADM models includes learning how to produce alternatives. The models can create the alternatives in practically all MODM models automatically. In most MADM circumstances, however, human generation of alternatives is required. Multiple objective linear programming (MOLP) and other multiobjective programming methods are used to tackle multiple-criteria decision-analysis problems.

Distinct from traditional single criteria monetary models, MCDA techniques allow stakeholders to compare options across many dimensions (Belton and Stewart, 2002, 2010). The goal in MCDA is to provide a procedure for the ordering of options in terms of preference. Distinct from traditional single criteria monetary models, MCDA techniques allow stakeholders to

compare options across many dimensions (Belton and Stewart, 2002, 2010). An aggregation procedure is applied to rank alternatives that are evaluated to reflect the stakeholders' objectives (Belton and Stewart, 2002, 2010).

The development and application of MCDA techniques can be traced to the work of Pareto (1896), Kuhn and Tucker (1951), Koopmans (1951), Charnes and Cooper (1957), Charnes et al. (1955, 1978); and Wierzbicki (1980). In the 19th century, Vilfredo Pareto (Pareto, 1896) introduced the concept of efficiency for measuring trade-offs between decision alternatives.

Several modifications took place. Koopmans further modified Pareto's work in 1951. Koopmans's work resulted in the introduction of the theory of efficient and non-dominated vectors (Koopmans, 1951). The Markowitz Portfolio theory is anchored on the theory of efficient and non-dominated vectors (Markowitz, 1952).

The GP linear model developed by Charnes and Cooper abetted the popularity of MCDA techniques. In 1957, Charnes and Cooper extended the theory developed by Koopmans by applying their GP linear model in the field of operations research. The first notable application of MCDA modelling was by Ignizio in 1962, who used the GP technique in designing and placement of arials used in launching the second stage of the Saturn V rocket used in the Apollo programme in the 1960s and 1970s (Ignizio, 1985).

In 1976, Keeney and Raiffa provided the first complete exposition of the MCDA application (Keeney, 1977). Keeney and Raiffa developed a practical MCDA theory based on the multi-attribute value theory for analysing decisions with multiple and competing objectives. The approach developed by Keeney and Raiffa in 1976 and later updated in 1993 is still relevant today. Their main objective was to promote the application of MCDA and the years following the publication of their work saw increased use of MCDA techniques to solve both the private and the public sector problems (Keeney and Raiffa, 1993). Today, the art of MCDA has expanded in many directions in the field of scientific operations research and decision science. MCDA techniques are used to evaluate socio-economic systems, ecological systems, project sites, private sector investments and highway project investments.

3.2 MCDA process and problem structuring

The MCDA process involves establishing alternatives, criteria for selection, and techniques for measuring each criterion and deriving weights for each criterion. According to MCDA literature, the procedure adopted in MCDA is described in nine steps summarised in Figure 12 (Belton and Stewart, 2002, 2010; Hostmann et al., 2005).

The decision aid procedure outlined in Figure 12 highlights four distinctive steps. The preliminary step involves the definition of the problem, together with the constraints faced to formulate alternatives. All MCDA procedures are heralded by problem structuring. Belton and Stewart (2010) best describe the link between MCDA and problem structuring.

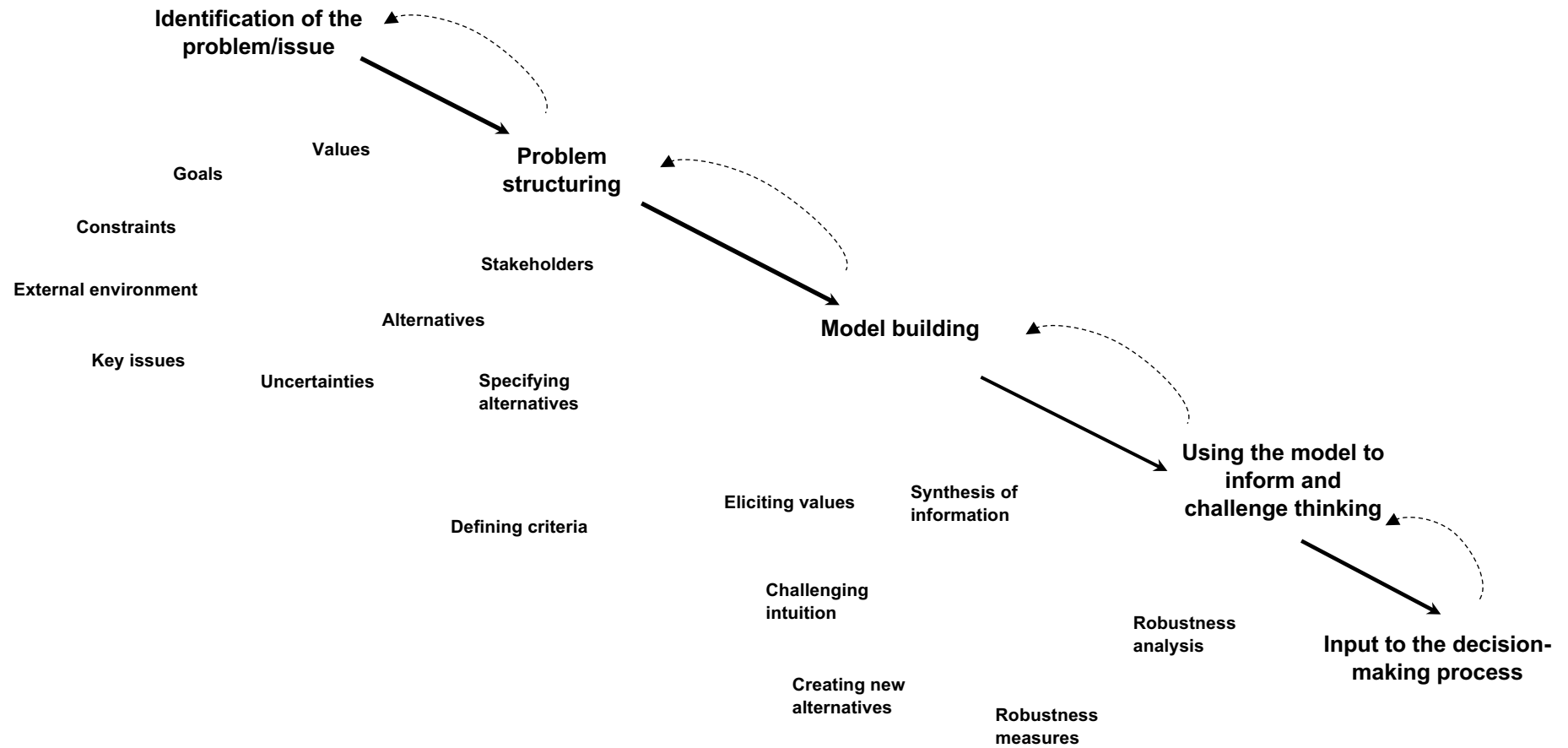
The MCDA process commences with problem identification, followed by the problem structuring phase. Stakeholders to the problem are then identified. The stakeholders may be represented by a group of decision-makers or a panel of experts. The decision-making team will then agree on a set of alternatives to solve the problem, goals and constraints, together with crucial issues and uncertainties. In the next stage, the analyst constructs the decision model for assessing the problem with input from the decision-maker(s).

A decision-maker in the context of the study and MCDA theory refers to an individual or group seized with the formulation and implementation of strategic organisational decisions while accounting for several variables, such as constraints and the number of stakeholders involved and information available. On the other hand, in the context of the present study, a stakeholder refers to an individual or a group of individuals who are likely to be affected by the outcome of a decision (s) taken by a decision-maker (s).

Once a model has been agreed upon, the decision team will synthesise the information and the results obtained. Sensitivity analysis is conducted to test the robustness of the model before a final decision is taken. As shown in Figure 12, it is worthwhile noting that this process is iterative, meaning it can be repeated several times until consensus is reached. The decision-maker(s) participate in all three phases.

The development of an evaluation matrix is a critical element in MCDA. Key components of the evaluation matrix include the definition of actors, formulation of alternatives, criteria selection and evaluation of actions according to the requirements. This crucial step must be done correctly to reduce inconsistencies. If done improperly, the reliability of the resulting outcomes will be weak and rejected by stakeholders in the decision.

Figure 12: MCDA process and problem structuring



Adapted from Belton and Stewart (2002), Eden and Ackermann (2006), Rosenhead and Mingers (2004)

In formulating alternatives, the proposed options should not be viewed as a silver bullet to the problem and should not be expected to address all aspects. One way to solve the problem is by formulating options alongside the PESTEL (political, economic, social, technical, environmental and legal) technique. Equally important and another area of contestation is criteria selection. According to Bouyssou (1990), to avoid bias and incompleteness, the methodology for determining criteria must meet the following five requirements:

1. The choice of evaluation criteria must be *legible*, viz, an adequate and a small number of criteria must be adopted;
2. The selection of evaluation criteria must be *operational*, meaning that it must be acceptable to all actors;
3. The evaluation criteria must be *exhaustive*, viz, the choice must consider all vital vantage points;
4. The selection of evaluation criteria must be *monotonic*, viz., partial preferences must be consistent with the main preferences expressed on options; and
5. The selection of evaluation criteria must be *non-redundant*, avoiding double counting.

The third process involves the assignment of criteria weights. There are various techniques for defining criteria weights. There are three types of approaches that are commonly employed. These methods are comprised of subjective weighing, objective weighing and combination weighing. According to Belton (1990), the “swing weights” method developed by Goodwin and Wright (1991) is one of the best techniques for determining weights. Notably, the selected technique for defining and determining criteria must satisfy the reliability test and must be easy to understand.

The fourth distinctive stage in MCDA is the aggregation of performances. The stage encompasses determining and selecting the MCDA technique best suited to the problem. There are over a hundred MCDA techniques which differ in many aspects. These aspects range from theoretical foundations and the form of results obtained. The eight-step process is discussed in detail below.

Step 1. The decision context

The first step is deciding the usefulness of MCDA to the problem at hand. This stage establishes the aims of the MCDA framework. Stakeholders and decision-makers to the problem are identified at this stage. This stage also establishes the objectives of the decision-making body and the level of involvement of the key player and stakeholders in the analysis.

The decision analyst must then create a socio-technical framework to guide the MCDA's execution. Facilitated focus group workshops are one method of accomplishing this (McLafferty, 2004). Two questions are answered by the method. The social element answers the question, "when and how should stakeholders be engaged?" whereas the technical element answers the question, "what form of MCDA should be used?".

As part of the first stage, the decision analyst considers the context of the appraisal. This action entails unpacking the current situation and establishing the goals. Commonly used situational analysis tools include the PESTEL technique, the SWOT (strengths, weaknesses, opportunities and threats) analysis tool and problem structuring techniques (Ackermann and Eden, 2010).

Step 2. Identifying and selecting options to be evaluated

The challenge in options analysis is the temptation to rely on pre-determined options. The process of options selection is susceptible to human error and bias. As a result, the model recommends that when applying the MCDA technique to the decision-making problem, whether options exist or not, as is the standard practice in the public sector, the decision analyst should modify and add options as part of the analysis. Fundamentally, what the MCDA does is that it stimulates the creative thinking process of participants. This iteration helps in refining and the development of further options.

Step 3. Criteria for assessing outcomes

At this stage, the decision analyst and the decision-maker(s) identify the criteria for measuring performance and choices. The criteria selected must assist in addressing the objectives and articulating how options create value. Commonly used criteria include numerical measures, which also include monetary valuation, ratings and qualitative descriptions.

In MCDA, selected criteria should always represent the concerns of all stakeholders. This means that in collaboration with the decision-maker(s), the decision analyst is required to develop a hierarchy that organizes and clusters criteria. At this stage, the analyst working with the decision-maker(s) prepares a value tree for objectives (Von Winterfeldt and Fasolo, 2009). Value trees are useful in structuring criteria (*Ibid*).

It's important to understand the distinction between objectives and criteria. The framework for evaluating alternatives is made up of objectives and evaluation criteria. In the context of this study, objectives are defined as a point of concern and the preferred direction of change, in which more is preferable to less. In contrast to criteria, as used in MCDA and the context of

the present study, refers to the means used to compare alternatives, expose trade-offs, and characterize the degree to which different alternatives are expected to meet objectives.

Step 4. Scoring the options

Each alternative is assessed against a given set of criteria identified in the previous step at the scoring stage . Each possible outcome is also evaluated as part of the scoring stage. The implications of each option must be clearly defined and scored on the criteria. The relative importance of decision-makers' choices for an outcome is assessed using scales. The weighted score is then computed across the preference scales, checking for consistency.

Step 5. Weighting

Each criterion must be assigned weights to show the relative importance of the criterion to the decision. Weights represent a compromise between criteria. These weights aggregate scores on each criterion to ascertain the total value. The process is synonymous with the procedure for setting exchange rates, where ratings on different criteria represent value. According to Belton and Stewart (2010), the swing weights method described by Goodwin and Wright (2001) provides the best procedure for determining weights. Belton (1990) provides a further discussion of weighting the criteria. When using local scales as the predominant scoring system, it is necessary to use the swing weights method. Other analysts employ compositional and decompositional techniques to elicit weights.

Step 6. Examining the results

The examination of the results process entails the real-world testing of results for validity, impact on the organisation and recipients and the future. The results from the assessment are examined at this stage for consensus building and making recommendations. The option with the better overall weighted score is selected .

Step 7. Sensitivity and robustness analysis

Sensitivity and robustness analysis is undertaken to check the impact of changing preferences and weights on the overall ordering of alternatives. New alternatives are introduced at this stage if deemed necessary. The analyst repeats this process several times and, in the end, develops a requisite decision model (Phillips, 1984). Phillips (1984) further posited that sensitivity analyses facilitate new insights into the problem. Sensitivity analysis, therefore, plays an essential role in resolving differences among stakeholders with competing interests. Also, robustness analysis is conducted to test the sturdiness of the model to improve decision quality.

Step 8. Policy conclusions and recommendations

The last step entails making policy conclusions and recommendations. The decision-maker(s) adopts the recommendations for policy formulation.

3.3 Multi-criteria decision analysis techniques

There are three broad categories of MCDA, namely the GP school. Outranking school and value/utility techniques Belton and Stewart (2002). The three types are discussed in detail below.

3.3.1 Multiobjective optimisation

Multiobjective optimisation is an MCDA technique for solving problems with multiple objective functions that must be maximized or minimized. The method generates a set of answers that define the optimum compromise between competing goals. According to Miettinen (2012), there are four types of multiobjective optimisation techniques: no preference, *a priori*, *a posteriori* and interactive multiobjective optimisation techniques.

In *a priori*, the decision-maker expresses preference information prior to the optimisation. Common examples of *a priori* techniques include the lexicographic, goal programming and the utility function. (Hwang and Masud, 2012). In a *a posteriori*, the decision-maker expresses preference information after being informed about the trade-offs among non-dominated solutions (*Ibid*). Using the interactive technique, the objective functions and constraints and their prioritization are obtained by requesting user feedback on preferences at multiple points during the execution of an algorithm (*Ibid*).

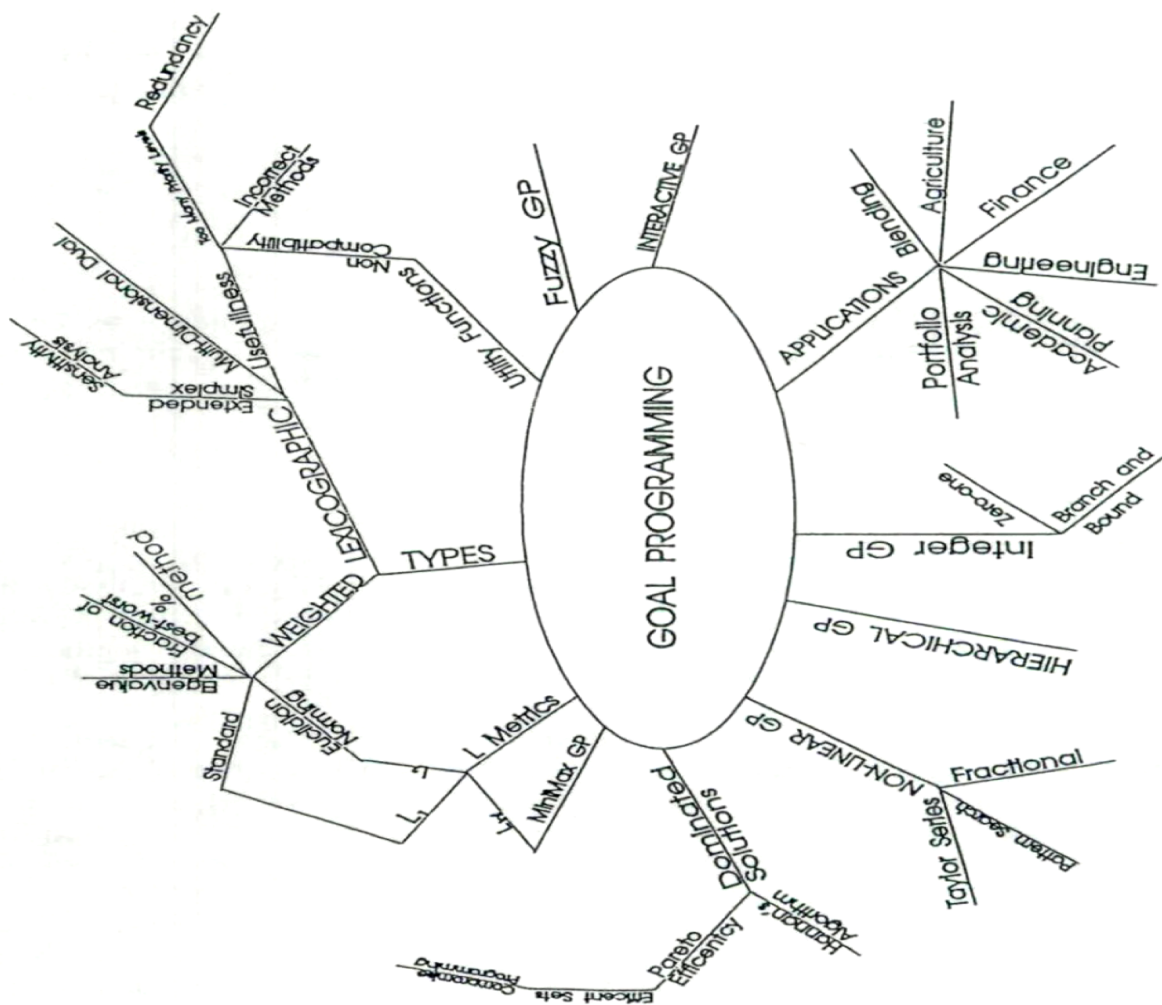
In literature, a crucial distinction is made between implicit and explicit approaches in multi-objective optimisation (Andonegi et al., 2021). The implicit approach uses information obtained from the decision-maker(s) during the solution process (Geoffrion et al., 1972). The implicit approach is based on of *a priori* technique discussed above, where the decision-maker(s) defines the aggregation function (Geoffrion et al., 1972). A well-known implicit technique is the GP approach.

Accounting for multiple objectives in combinatorial problems and at the same time finding Pareto-optimal solutions is hugely challenging. The use of explicit approaches is regarded as one of the ways available to deal with this challenge. Joseph et al. (2009) and Carwardine (2012) encouraged the use of explicit approaches such as the value function technique by empirically asking experts to avoid the mathematical challenge associated with implicit approaches (Lahdelma et al., 2000; Mendoza and Martins, 2006).

3.3.2 Goal programming techniques

GP models are premised on a decision analyst working with the decision-maker(s) to determine the alternatives that are considered closest to the achievement of a pre-determined goal (Hwang and Yoon, 1981; Yoon, 1987; Hwang et al., 1993). Figure 13 presents a graphical representation of GP topics according to Tamiz et al. (1995). A key element of GP formulations is the achievement function that measures the degree of minimization of the unwanted deviation variables of the goals considered in the model. Each type of achievement function leads to a different GP variant. The three oldest and still most widely used forms of achievement functions are the weighted (Archimedean), pre-emptive (lexicographic) and MINMAX (Chebychev) (Tamiz et al., 1995).

Figure 13: Graphical representation of goal programming topics



Source: Tamiz et al, 1995

GP technique is an extension of standard linear programming in which desirable levels of performance (labelled g_k) are specified by decision-makers for each objective k ($k = 1, \dots, k$) given set of constraints (Charnes and Cooper, 1961; Rifai, 1996). In obtaining any feasible solution, non-negative *deviational variables* are introduced, defined as d_k^+ and d_k^- . The objective in GP is to minimize the (weighted) sum of undesirable deviations as d_k^+ or d_k^- (depending on the goal). For each goal (g_k), at least one of the deviational variables must be equal to "0", such that $z_k + d_k^- - d_k^+ = g_k$; with z representing objectives k representing criteria/objectives which may be scenario related. The d^- and the d^+ superscripts indicate whether a goal is to be minimised, over, or underachievement of the goal priority. An optimal solution is attained when all the goals are reached as close as possible to their aspiration level while satisfying a set of constraints (Charnes and Cooper, 1961).

In some cases, decision analysts incorporate the simplified Chebychev Theorem into the analysis. Proponents (Charnes and Cooper, 1957; Benayoun et al., 1971; Yu and Zeleny 1975; Hwang et al. 1993), of the GP models, posit that the approach is best suited for the use of interactivity. In the linear programming technique postulated by Benayoun et al. (1971), a specific goal determines the ideal solution for each criterion. The technique uses Chebychev Theorem formulations. The formulation uses a relative range of normalised values for the weights converted to a convenient scale, e.g., 1-10.

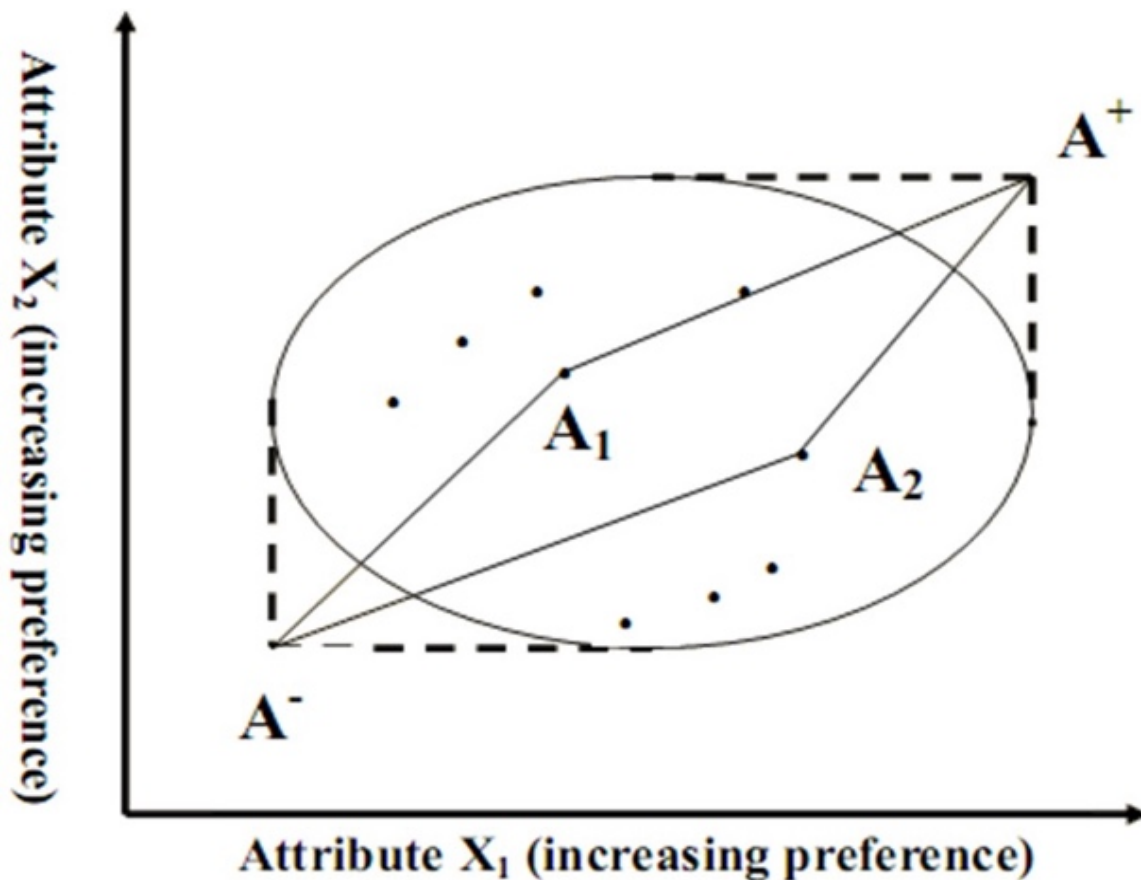
Benayoun et al. (1971) advocated that the concept of optimum solution be replaced with the concept of best compromise solution. This technique is referred to as the STEP technique (STEM). The Chebychev distance between an ideal point and the criterion space is reduced using the STEM technique. To alter the parameters of the distance formula and the feasible space, a normalized weighting strategy based on the decision-preferences decision-makers in the prior solution can be utilized. The STEM technique allows the decision-maker to find solutions and the relative importance of the goals.

According to Belton and Gear (1997), relative importance is the per cent improvement over the most important predictor. Relative importance is calculated by dividing each variable importance score by the variables' largest importance score, then multiplying by 100 per cent (*ibid*). At each iteration, the decision-maker can improve some objectives while sacrificing others. In addition, the decision-maker must state the maximum amount by which the goal functions can be compromised, while trade-offs on other factors must be considered.

Another variation of the GP approach is the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) technique. Hwang and Yoon (1981) first proposed the TOPSIS

technique in 1981. The essential principle in TOPSIS is that the chosen alternative should be the furthest from the perfect solution and the closest to the negative-ideal solution (Figure 14).

Figure 14 : Basic concept of TOPSIS method



Key: A^+ : Ideal point, A^- : Negative-ideal point

Source: Yoon (1980); Hwang and Yoon (1981)

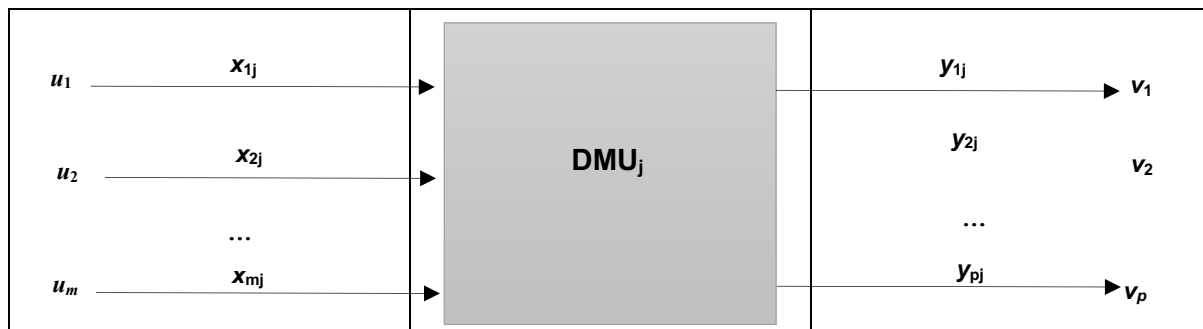
The non-ideal option adjoining the ideal alternative is selected. The GP procedure is well-suited for the use of interactivity. Because of these properties, the technique has been used in unravelling energy resource planning problems (Ramanathan and Ganesh, 1994; Cherni et al. (2007). The GP technique is capable of dealing with large-scale issues. The technique is also suitable in cases where the number of alternatives available is very large, and the primary goal is narrowing the search for fewer options. GP models, therefore, can handle large-scale problems.

3.3.3 Data envelopment analysis

First introduced by Farrell back in 1957, data envelopment analysis (DEA) is a linear programming-based technique for evaluating the relative performance of entities with multiple

inputs and outputs, known as decision-making units (DMUs) (Farrell, 1957; Charnes et al., 1978). The technique calculates the efficiencies of DMUs.

Figure 15: Structure of DMU



Source: Charnes et al., (1978).

As shown in Figure 15, a DMU can be defined as any entity that can transform measurable inputs to produce quantifiable outputs. For instance, the productive efficiency of an energy-producing entity can be measured according to the energy it consumes per unit of output of energy generated. In recent times, DEA has been applied to decision-making environments. These include banking (Paradi and Zhu, 2013), transport (Leal et al., 2012) and health (Jing et al., 2020; Ngobeni et al., 2020). There are also several DEA studies in energy and environmental economics (Duan et al. 2016), (Iribarren et al., 2014), (Lins et al., 2012), (Ren et al., 2014), (Yan et al., 2017), (Gan et al., 2017), (Sueyoshi and Wang, 2017) and (Liu et al., 2017).

According to Seiford and Thrall (1990), the main advantage of the DEA technique is that users do not necessarily need to comprehend the underlying functional relationships and outputs in DMUs. The main drawback of the DEA technique is that the measured efficiencies of DMUs are relative and only attain meaning in comparison to other elements, i.e., it is impossible to describe the relationship between inputs and outputs in DMUs. The DEA technique is more applicable to management sciences, where DMUs can be identified and defined and less relevant to evaluating systems such as technologies.

It's worth mentioning that DEA was not created to be used as an MCDA tool or for evaluating different policies for the sake of choice. According to Belton and Stewart (1999), DEA is a method for "extracting as much as possible from "objective," historical data without resorting to subjectivity." In contrast, MCDA aims to elicit, comprehend, and regulate value judgments. The DEA is considered a good technique for monitoring and control, whereas the MCDA is suitable for evaluation and selection. According to Belton and Stewart (1999), several

applications cross these boundaries, and there is growing interest in the field of DEA in adding value judgments in some analyses.

Belton and Stewart (1999) suggest that there are many ways in which the two approaches can be used complementarily and that each can learn important lessons from the other. On the one hand, Belton and Stewart (1999) suggest that MCDA techniques could benefit from DEA by taking a step back and considering what can be learned from available objective data before venturing into complex value judgements. On the other hand, DEA practitioners should seek to learn from the extensive experience of MCDA analysts and researchers in eliciting and handling value judgements (Belton and Stewart (1999)).

3.3.4 Outranking techniques

The outranking methods, also known as the French school, originated in Europe in the 1960s under the works of Bernard Roy and Jean-Pierre Brans. Under outranking approaches, alternatives are compared pairwise against a given criterion. Outranking models are structured to determine to what extent one alternative outranks another. Outranking models are anchored on the argument that, after taking criteria into account, if it can be established that alternative **a** is better than alternative **b**, then it is concluded that alternative **a** outranks alternative **b**. (Roy, 1990).

According to Belton and Stewart (2002), popular outranking techniques include the Preference Ranking Organisation Method for Enrichment of Evaluations (PROMETHEE) and the Elimination Choice Translating Reality (ELECTRE). The ELECTRE technique was first developed by Benayoun et al. (1966). Further developments and modifications later saw the introduction of ELECTRE-I by Roy (1968). The technique was further modified into a variety of variants.

The widely used forms are ELECTRE IS, ELECTRE-II, ELECTRE-III and ELECTRE-IV. In literature, most of these techniques have been combined with fuzzy sets by academics. According to Roy and Bouyssou (1993), ELECTRE I and IS are designed for selection problems, whereas ELECTRE II, III and IV are used for ranking problems. The ELECTRE technique is widely endorsed in the academic literature as an alternative to the value and utility function models. Outranking techniques are useful when it is possible to reduce alternatives to a smaller number (Belton and Stewart, 2002).

The ELECTRE does not produce a single best alternative. The ELECTRE technique accounts for uncertainty and vagueness and is usually applied to discard unfavourable options and

constrict the other options to a restricted and smaller set. A growing practice is the application of a different MCDA technique to select the best alternative from a limited set resulting from ELECTRE (Belton and Stewart, 2002; Pohekar and Ramachandran, 2004).

The ELECTRE technique has been widely applied to financial research and energy sector problems (Pohekar and Ramachandran, 2004). Following the Computer-Aided Rehabilitation of Water Networks Project (Sægrov, 2005) and Computer Aided Rehabilitation of Sewer Networks Project (Sægrov, 2006), ELECTRE techniques have gained popularity in Europe (Kabir et al., 2014). They have been utilized for sewer rehabilitation planning (Baur et al., 2005; Carriço et al., 2012), as well as urban stormwater drainage management (Moura et al., 2006; Martin et al., 2007) and urban flood control (Moura et al., 2006; Martin et al., 2007). (Sabzi and King, 2015). Opponents of the technique posit that the ELECTRE procedures and results can be challenging to explain to non-specialists, and outranking makes it challenging to identify alternatives directly.

Another widely used outranking technique is the PROMETHEE technique (Brans and Vincke, 1986) and later Mareschal, Brans and Vincke (1984). The PROMETHEE technique is a branch of the ELECTRE technique (Akafpour and Hamidi, 2013). It is argued that the PROMETHEE technique is easy to apply. The main shortcoming of the technique is that the technique does not provide a precise technique for assigning weights (Pohekar and Ramachandran, 2004).

3.3.5 Value/utility function approaches

A utility function represents individual preferences for commodities or services that are not directly monetary valued. In other words, it is a relative measurement of how strongly someone desires something. The measure of value is utility. On the other hand, a value function of an optimization problem, on the other hand, delivers the value obtained by the objective function at a solution while just relying on the problem's parameters (Bouyssou and Vansnick, 1988).

Peter Fishburn (1967) first described the theoretical foundations behind additive utility functions in 1967 after years of research in the numerous fields of operations research. Through his work, Fishburn (1967) reviewed 24 techniques of estimating additive utility formulations for risky and non-risky multiple-factor decision situations, and he used many examples to illustrate the techniques.

Value function approaches are judgment oriented and are useful in presenting a full ranking of alternatives (Keeney, 1992, 1993). Additive scoring is the dominant value function approach

as they are easy to understand and very useful at the same time. Equation 1 provides a summary of the formulation.

$$S_i = w_1s_{i1} + w_1s_{i1} + \dots w_ns_{in} = \sum_{j=1}^n w_js_{ij}\dots \quad \text{Equation 1}$$

S_i expresses the overall performance value for option, the preference for option i on criterion j is represented by s_{ij} and the weight for each criterion by w_{ij} ; n represents is the overall score for each option. The process is repeated iteratively, as highlighted in Figure 12.

The AHP (Saaty, 1980), the Multi-Attribute Utility Theory (MAUT) (Fishburn, 1967; Fishburn and Keeney, 1974) and the MAVT approaches are the three most popular value function aggregation techniques (Velasquez and Hester, 2013). Unlike other value function techniques, the AHP technique makes use of pairwise comparisons to elicit the criteria weights from decision-makers. The AHP technique allows the use of both qualitative and quantitative criteria on the same preference scale (Saaty, 1980). Also, the AHP is not data-intensive and considered easy to apply and can be easily adjusted to handle different sized problems.

Theoretical disputes limit the applicability of the approach. Critics argue that the AHP technique is too basic. The procedure is considered only useful for its pairwise comparison. Additionally, opponents also argue that the interdependence between criteria and alternatives presents problems. According to Velasquez and Hester (2013), the AHP technique is also susceptible to rank reversal.

The MAUT theory (von Winterfeldt and Edwards, 1986; French, 1988) is related to the MAVT approach. The MAUT technique, however, uses strong assumptions to safeguard additivity. The technique is regarded as complex to apply in the real world as it requires lots of input and preferences need to be precise. It is against this background that the MAVT is measured as the most preferred technique when dealing with real-life decision problems (Løken, 2007). The MAVT technique (Keeney and Raiffa, 1976) has been widely applied to decision-making (Munda, 2005). The “strong” assumptions for additivity in MAUT are in the context of uncertainty. If the expectation is not required MAUT, defaults to MAVT, where additivity requires only preferential independence⁷. In the next section, we discuss the MAVT approach in detail.

⁷ “In decision analysis, specifying a multi-attribute value or utility function requires assessments from a decision-maker. This can be difficult because it requires the determination of an n-dimensional function. To simplify this, researchers have established conditions on preferences under which the form of the value or utility function is simplified. One of these conditions is *preferential independence*”. (Simon et al., 2014)

The widely used aggregation form of MAVT is the additive value function (Belton and Stewart, 2002; Hostmann et al., 2005) presented in Equation 2.

$$V_s = \sum_{k=1}^m w_k v_{sk} \quad \text{Equation 2}$$

Where, V_s represents the overall performance value for alternative s , computed at the weighted sum of the performance on m criteria. Criterion k is weighted with the weight w_k . v_{sk} represents the preference value of alternative s for criterion k .

MAVT is a general value function used in unstructured problems (Fishburn, 1967; Keeney and Raiffa, 1976). The MAVT approach is a compensatory technique, and the decision rule within MAVT is a complete compensatory one. A compensatory decision-making method balances the good and negative characteristics of the options under consideration, allowing positive characteristics to compensate for bad characteristics. When the final values for attributes are computed, negative attributes can be compensated for by equal or higher value positive attributes in compensatory judgments. For example, because it is a direct journey, a plane ticket that costs R450 more (negative characteristic) may eventually be the superior decision (positive attribute). The MAVT technique can be applied to problems with a limited and discrete set of alternatives, which can be appraised based on contradictory objectives (Belton and Stewart, 2002). In an additive model, the objective function represents the additive aggregation function. An additive measure, also known as a completely additive measure, can be aggregated along any of the dimensions included in the measure group that contains the measure (Kolesárová, 2019).

Other value measurement techniques include the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) (e Costa and Vansnick, 1994); the Preference Assessment by Imprecise Ration Statements (PAIRS) (Salo and Hämäläinen, 1992), the grey relational technique (Deng, 1985) and the fuzzy set methodology (Zadeh, 1996).

3.4 Chapter conclusion

This chapter provided a summary of MCDA techniques. The investigation observed that MCDA techniques are useful for solving complex decisions. These decision-support techniques are suitable for unravelling problems characterized as a choice among several alternatives. Additionally, the study noted that a key aspect of MCDA decision-support techniques is that they force the decision-makers to think, enquire, fine-tune, test and focus on what is important logically, consistently and iteratively (see Figure 12)

The study concludes that the usefulness of MCDA techniques is reinforced by their ability to decompose problems into smaller parts, the examination of each part and the integration of the parts to yield acceptable solutions. The research further concludes that, in group settings, MCDA techniques are useful in assisting stakeholders to the problem to engage collaboratively on a decision opportunity (the problem) and trade-offs among alternatives in a manner that permits all members to reflect the values that each participant views as imperative.

Lastly, the review concludes that no single MCDA technique can be considered superior to another as its use depends on the circumstances and decision. There are many ways in which the different MCDA techniques can be used complementarily and can supplement the shortcomings of the other in real-life applications.

In the next chapter, we extend the theoretical analysis by looking at empirical applications of the MCDA specifically to low-income household energy planning problems with a particular focus on rural areas and informal urban settlements.

CHAPTER 4

A REVIEW OF EMPIRICAL STUDIES

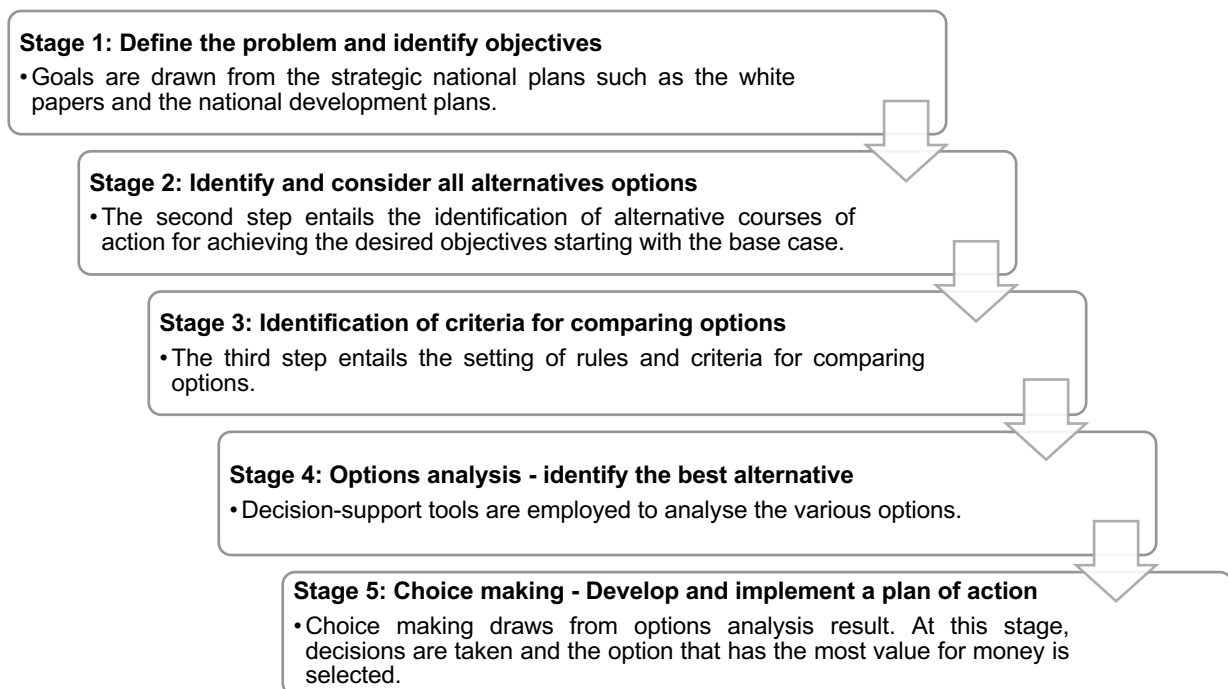
4.0 Introduction

This chapter reviews relevant literature in rural energy supply planning, including decision-making criteria and decision processes. The chapter tackles the second objective of the study and probes empirical studies on MCDA and sustainable rural energy planning and development. The author explored the topical issues in MCDA and established the link between empirical literature and this present study. The chapter provides both a descriptive summary and a critical analysis of the salient features of existing studies. The literature review was conducted to identify inconsistencies, gaps and limitations in existing studies, conflicts in previous studies, open questions left from other research and identified the need (justification) for additional research – the present study.

4.1 Decision making in the public sector

In the public sector, decision-making takes the form of evaluation of choices and outcomes. Typical forms of analysis in public sector investment decision-making include economic appraisal and financial analysis. These approaches are based on monetary valuations of impacts (costs and benefits). Figure 16 summarises the decision-making process.

Figure 16: Decision-making process



Source: Adapted from Guo (2008)

4.2 Monetary based project appraisal techniques

This section outlines the commonly used monetary-based decision-support systems for project appraisal in the public sector. These techniques include financial analysis, cost-effectiveness analysis (CEA) and cost-benefit analysis (CBA).

4.2.1 Financial analysis

Financial analysis in the public sector takes the form of an assessment of the cash flow impact of options with a particular emphasis on costs, revenues, and a project's ability to cover operational costs and debt service. Financial analysis is used to test the affordability of a project to the fiscus and users. The World Bank recommends that in addition to affordability, projects should be assessed, considering the full lifecycle costs (Unpublished World Bank and National Treasury internal document, 2017). For example, the Municipal Finance Management Act (Act 56 of 2003) (MFMA) requires that all municipal capital projects should generate sufficient ongoing revenues to cover ongoing costs. An extract of the MFMA on infrastructure projects is presented in Textbox 1.

Textbox 1: MFMA clause on infrastructure projects

“Municipal Finance Management Act

Capital projects

19.

- 1) *A municipality may spend money on a capital project only if -*
 - (b) The project, including the total cost, has been approved by the council.*
- 2) *Before approving a capital project in terms of subsection (1)(b), the council of a municipality must consider-*
 - (a) the projected cost covering all financial years until the project is operational; and*
 - (b) the future operational costs and revenue on the project, including municipal tax and tariff implications.”*

Source, Municipal Finance Management Act, 2003

Financial analysis draws on the principles of the time value of money and life-cycle costs. Future cash flows are discounted to a present value using a discount rate. A hurdle rate is used as the proxy discount rate, which equates to the weighted cost of capital. The process of discounting cash flows applies equally to CBA. The main difference is that CBA employs the social discount rate.

The decision rule in financial analysis is four-fold. In the first instance, all projects with a positive net present value (NPV) are accepted. Secondly, if several projects have positive NPVs, the decision rule is “accept the project with the highest NPV.” The third rule is “accept all projects whose calculated internal rate of return exceeds a pre-determined and agreed

hurdle rate. The fourth rule relates to life-cycle costs. An option with the least per unit cost is accepted. In many jurisdictions, financial analysis is often legislated and is used as the first line of defence when screening projects. CEA and CBA techniques are preferred where a project or a programme fails the financial feasibility test.

4.2.2 Cost-effectiveness analysis

CEA involves the assessment of the financial and non-financial costs of mutually exclusive alternatives given a similar objective. The goal in CEA is to select the least cost option without compromising on quality. Costs are monetised and measured based on actual expenditures as opposed to opportunity costs. The benefits in CEA are, however, not monetised and but quantified physical measures such as project outputs are used to measure the net benefit. CEA makes use of shadow market prices from some marketed inputs. Shadow pricing is employed to account for costs of intangible commodities and services that are difficult to assign a monetary value but that must nonetheless be monetarily quantified for carrying out the analysis. Shadow pricing is, however, fraught with problems. Shadow pricing is generally considered to be subjective and inexact. The decision rule in CEA is to rank projects from highest to lowest effectiveness. Projects with the lowest cost-effectiveness ratio are deemed justifiable.

4.2.3 Cost-benefit analysis

CBA entails the evaluation of all monetary and non-monetary costs and benefits of alternatives. Akin to financial analysis, CBA is legislated in many countries and is grounded in utilitarian and welfare economic theory first advocated by Jeremy Bentham and later modified by John Stewart Mill in the 18th and 19th centuries (Bentham and Mill, 2004). The field of welfare economics justifies government involvement in the economy in the first place. The government intervenes to address private economy market failures such as imperfect competition, information asymmetry and the presence of externalities.

The goal in CBA is to improve Pareto efficiency by implementing projects with the highest benefit-cost ratio. The decision rule in CBA is two-fold. First, projects with the highest economic NPV (ENPV) are selected. Pareto efficient projects are selected, i.e., projects with the highest benefit-cost ratio. According to Thomopoulos et al. (2009), this allows decision-makers to compare options based on a single indicator.

There are two conventional approaches for monetising costs and benefits under the CBA framework. These are the hedonic pricing method and the stated preference approach.

Hedonic models are standard in real estate economics. The assumption house prices reflect homeowner's valuations for such challenging to monetise features like the safety, quality of the environment and access to schools, hospitals and transportation modes. The market values are then estimated using statistical hedonic regression. The hedonic technique is also known as the revealed preference technique. On the other hand, the stated preference techniques estimate the direct consumer valuations of environmental impact. Monetary values are derived from people's willingness-to-pay values, given specific changes.

The major drawback of the CBA methodology is that even using procedures such as stated preference or hedonic pricing, it is practically impossible to correctly establish monetary values of non-marketed impacts making the CBA technique susceptible to optimism bias⁹ (Cantarelli et al., 2010). Secondly, the CBA technique's effectiveness is affected by the non-availability of relevant and noise-free data. In some cases, data can be too expensive and cumbersome to collect. Thirdly, selecting an appropriate social discount rate presents problems, especially in cases where a blanket rate is applied across all projects, programmes and sectors. The challenge of using a blanket social discount rate across the country is the sensitivity of the discount rate. (Nijkamp and Van Delft, 1977; Thomopoulos et al., 2009).

The CBA technique is popular in guiding public policy in many countries (Zerbe and Bellas, 2006). The BCA approach is a straightforward method that considers all gains and losses to society. Standard practice has been to employ MCDA techniques as an extension of CBA (Dodgson et al., 2009).

4.3 Evaluation techniques based on multi-objective optimisation

Linear and non-linear programming techniques have been widely used in solving combinatorial problems. Given a finite collection of items and a set of constraints, a combinatorial issue entails finding an object from the collection that meets all of the constraints (and possibly optimizes some objective function) (Hoo and Stützle, 2004). Combinatorial problems are common and have a wide range of applications (Mehta et a, 2007), land use planning (Stewart et al., 2004), research and development project selection (Stewart, 1991), water resources planning (Stewart and Scot, 1995) finance (Mansini et al., 2014) and transport (Dujardin et al., 2015).

The benefits of using multi-objective optimisation techniques to confront energy resource planning problems have been recognised in the literature. (Hobbs and Meier, 1994). This

⁹ A cognitive bias that causes a person to believe that there less likely to experience an adverse event.

recognition is because energy resource planning problems are also combinatorial, given that choices can be made by merging several smaller decisions. This condition makes the number of both feasible and unfeasible actions too large to employ exhaustive techniques.

4.4 Summary of empirical studies

Literature for the study was searched using four electronic bibliographical databases¹⁰; namely the Elsevier Science Direct, JSTOR, Google Scholar and Springer. The search strategy involved combining English search terms for the research objective (“multi-criteria decision analysis, multi-objective optimisation, decision problems, and energy system”) and search terms regarding the dimensions of other objectives and the research framework (low-income household energy consumption in South Africa, rural energy development). In selecting literature, the following criteria was used:

1. Type of energy supply planning and evaluation decision;
2. Impact factor and citation count statistics;
3. Publication date – publications between 1990 and 2021;
4. Country; and
5. MCDA technique employed.

Publications that meet the above criteria were selected for review. Studies on sustainable energy development and strategic low-income household energy supply option evaluation employing various MCDA techniques were given a substantial weighting in the study selection process. The length and breadth of both MCDA methodologies and decision types were also crucial considerations in the selection of empirical research. The studies included in Table 6 are examined in greater depth, highlighting current issues, the current study’s contribution, noted limitations, and justification for inclusion in the current study. The literature review offers a synthesis of the following:

- Decision-maker involvement;
- Strengths of the approach used;
- Weaknesses of the approach used; and
- Lessons learnt for the pursuit of the present study.

Table 6 presents a summary, in chronological order, of the salient characteristics of selected and reviewed studies.

¹⁰ Web search engines that index the full text/metadata of scholarly literature across various publishing formats and discipline.

Table 6: Summary of major empirical studies

Author (s)	Country	Research objective	Topical issues	Contribution to the present study	Justification for inclusion
Jones et al. (1990)	UK	Examination of the UK energy policy.	Structuring energy problems incorporating renewables and formulating group decisions and public participation.	The paper describes in detail the process of developing a SMART (simple multi-attribute rating technique) model to address energy planning problems.	The study made predictions on the future role of renewable energy technologies, these predictions have been proven to be true given the current role renewable energy technologies are playing in many countries' energy mixes including South Africa (see also Stein, 2013).
Ramanathan and Ganesh (1994, 1995)	India	Evaluation of off-grid electricity generation technologies in low-income communities.	Assessment of household energy supply options.	The study demonstrates the strengths of multi-objective energy combination studies performed for assessing household energy supply options.	The studies helped in demonstrating the applicability of MCDA-based analysis to household energy supply systems. The model is popular among researchers. (Ehyaei and Bahadori, 2007; Jinturkar and Deshmukh, 2011; Trutnevte et al., 2011; Ahammed and Azeem; 2013).
Stewart and Scott (1995)	South Africa	Decision analysis in water resource planning.	Multi-criteria, water resource planning optimisation model.	The study demonstrates the strengths of multi-objective energy combination studies performed for assessing strategic decisions within water resource planning in South Africa.	The study has been applied to real-life water resource planning in South Africa (see Joubert et al. (2003). This application makes the research more relevant to the present study, given similarities in stakeholders to the current study problem.

Author (s)	Country	Research objective	Topical issues	Contribution to the present study	Justification for inclusion
Haralambopoulos and Polatidis (2003)	Greece	Evaluation of new energy technologies for Greece.	Structuring energy problems incorporating emerging technologies and formulating group decisions and public participation.	The normative decision-making framework developed helped illustrate the applicability of MCDA techniques in the analysis of comparable energy technologies and problems based on the prescripts from the investigation.	The study helped strengthen the argument that MCDA techniques are well suited for structuring, formulation and assessment of complex public policy issues.
Begić and Afgan (2007)	Bosnia and Herzegovina	Sustainability assessment of energy power systems.	Combination of single criteria analysis and multiple criteria decision aid techniques.	The study applies both single and multiple criteria analysis and proves the deficiency of sole criteria analysis.	The technique developed can work with limited information and the study has been empirically applied in the sustainability evaluation of sophisticated energy, mining and forestry where the information available is usually non-numeric, non-exact and non-compete (Afgan and Carvalho; 2008; Jovanović and Afgan, 2009; Tsoutsos et al., 2009; Kijevcanin et al., 2017).

Author (s)	Country	Research objective	Topical issues	Contribution to the present study	Justification for inclusion
Burton and Hubacek (2007)	UK	Evaluation of energy generation technologies.	Structuring energy problems incorporating renewables and formulating group decisions and public participation.	The framework applied was based on the combination of both implicit and explicit approaches. The study guides the present research on the combination of two approaches to structuring and formulating an energy access problem	The study fused both MCDA and CBA techniques to energy technologies evaluation; this makes the research more relevant to the present study.
Cherni et al. (2007)	Colombia	Evaluation of a set of appropriate energy options to fulfil local needs.	Assessment of low-income household energy supply options.	The study is particularly valuable for researchers seized with energy planning in developing countries such as South Africa, where some remote rural socio-economic and geographic features mirror those of remote Colombian rural areas.	The framework developed by Cherni et al. (2007) underpins similar reviews in Manantiales, Cuba (Cherni and Hill, 2009) and Jambalo, in the southwest of Colombia (Heano et al., 2012). The study by Heano et al. (2012) extended earlier work by Cherni et al. (2007) by incorporating robustness analysis. The model by Cherni et al. (2007) has also been empirically tested in remote rural areas in Africa, namely Tanzania, Rwanda and Malawi (Barry et al., 2011).

Author (s)	Country	Research objective	Topical issues	Contribution to the present study	Justification for inclusion
Lhendup (2008)	Bhutan	Assessment of alternatives for rural electrification.	Assessment of low-income household energy supply options.	Study essential to the present study, in particular in the identification of alternative energy supply options in a least-developed country with a scattered population. These are areas of interest for the present study identified in Hughes et al., (2017), explained in section 2.1.	Studied conducted in a low-income country with a scattered pattern of settlements and demonstrated the utilisation of a modest Microsoft Excel-based simple weighting MCDA technique and proves that it is possible to commission studies employing MCDA techniques using economical and straightforward software packages.
Buchholz (2009)	Uganda	Assessment of bioenergy systems.	Assessment of low-income household energy supply options.	The contribution and significance of this study to the present research lay in the application of different MCDA techniques to confront a specific problem and the realisation that regardless of the MCDA technique applied.	The study was conducted in a low-income country with a scattered pattern of settlements and demonstrated the utilisation of numerous MCDA techniques and proves that it is possible to commission studies employing many techniques.
Stein (2013)	US	Evaluation of electricity generation technologies.	Structuring energy problems incorporating renewables and formulating group decisions and public participation.	The decision-making framework developed helped illustrate the applicability of MCDA techniques in the analysis of comparable energy generation technologies.	Study findings validate earlier arguments raised by Jones et al. (1990), further strengthening the business case for the application of MCDA-based techniques to energy planning problems.

Author (s)	Country	Research objective	Topical issues	Contribution to the present study	Justification for inclusion
Van Blommestein and Daim (2013)	South Africa	Evaluation of residential energy saving (efficient) devices.	Assessment of energy efficiency and building energy management options.	The study is of significant importance to present, given its focus on energy technology evaluation in South Africa.	One of the very few studies employing MCDA thinking in the evaluation of energy efficiency devices in South Africa.
Nerini et al. (2014)	Brazil	Assessment of rural electrification options in the Brazilian Amazon.	Assessment of low-income household energy supply options.	The study was essential to the present study, in particular in the identification of alternative energy supply options in a least-developed country.	Studied conducted in a low-income country with a scattered pattern of settlements and demonstrated the utilisation of a modest Microsoft Excel-based simple weighting MCDA technique and proves that it is possible to commission studies employing MCDA techniques using economical and straightforward software packages.
Blanco et al. (2017)	Paraguay	Analysis of energy policy in a developing country.	Application of MCDA in emerging countries.	The study demonstrates the suitability of MCDA in emerging countries faced with the need to balance between competing demands given the high levels of social inequality, economic challenges and climate change and environmental challenges.	The study model developed is empirically applicable to several of the present study given the current energy access challenges faced by South Africa despite access to renewable energy resources such as high solar irradiation levels.

Author (s)	Country	Research objective	Topical issues	Contribution to the present study	Justification for inclusion
Trotter et al. (2019)	Uganda	Long term energy planning employing an optimisation technique.	Application of an optimisation technique long-term energy resource planning in a developing country.	The study was conducted in a country with little power infrastructure and considered renewable energy technologies.	The study was conducted in a developing country with low electrification rates. The study is also recent, meaning that it considered renewable energy technologies and the most current costs.

a. Jones et al., (1990), UK

According to the authors, at the time, the energy policy debate in the UK had become a contested issue characterised by differences of opinion among different stakeholders. The underlying motivation for the study by Jones et al. (1990) was to provide a platform for accommodating competing viewpoints. The authors conducted a study exploring the application of the simple multi-attribute rating technique (SMART) to strategic energy planning in the UK in 1990. The investigation predicted that renewable energy sources provide more benefits to society than non-renewable options. Subsequent studies (Stein, 2013) have revealed the significant role renewable energy will play in many countries, as Jones et al. (1990) postulated.

i. Decision-maker involvement

The decision-makers comprised a panel of 25 individuals from 16 organizations from the energy industry, political parties, government, pressure groups and trade unions. These were involved in the development of the model. The panel considered 15 energy policy attributes to evaluate five contrasting energy-policy options. The panel was instrumental in establishing both alternatives and criteria and was involved throughout the decision-making process.

ii. Strengths

The study by Jones et al. (1990) specifically addressed the main drawbacks of earlier studies by Keeney et al. (1987), which were restricted to the structuring of objectives only and the study by Hämäläinen (1988), which failed to provide a more formal framework for policy debate. The study supported the decision-making process and helped to strengthen the argument that MCDA techniques are well suited for structuring complex public policy issues.

iii. Weaknesses

The key constraint of this study was the MAUT procedure's technical limitations, particularly the usage of strong assumptions to ensure additivity, which demands a lot of input from the decision-maker and precise preferences (see also Section 3.3.5).

iv. Lessons learnt for the pursuit of the present study

In their modelling approach, Jones et al. (1990) used the SMART process for multi-attribute utility measurement, which offered significant direction for the current investigation. The SMART model created for this study was based on the SMART technique and a 10-step procedure for using the model in real-life situations. (Identifying stakeholders; identifying action choices; identifying attributes; identifying empirical indicators; ranking attributes; rating

attributes in importance-preserving ratios; scaling ratings; scoring alternatives on each attribute; calculating utilities; and ultimately, decision-making.).

b. Ramanathan and Ganesh (1994, 1995), India

Studies by Ramanathan and Ganesh (1994) and Ramanathan and Ganesh (1995) rank among the first multi-objective energy combination studies performed for assessing household energy supply options in India. The authors applied the GP technique to evaluate five¹² electricity generation technologies in the first study. The results of the model developed by Ramanathan, and Ganesh and sensitivity analysis conducted recommended stand-alone PV and diesel systems for low-income households. In a follow-up study in 1995, the authors developed an enriched and integrated AHP and GP model to evaluate seven energy sources used for lighting households in India.

i. Decision-maker involvement

In the first study, given the technical nature of the investigation, no decision-makers were involved establishing the nine energy, economy and environmental criteria for the evaluation of five contrasting electricity generation technologies. Parameters used in the study were based on academic literature and publications on energy supply technologies. In the second study in 1995, a panel of experts was established and participated in developing an integrated model. The panel considered the nine energy, economy and environmental criteria for the evaluation of seven contrasting energy alternatives for lighting. The panel was instrumental in establishing both alternatives and criteria and was involved throughout the decision-making process.

ii. Strengths

The two studies by Ramanathan and Ganesh in 1994 and 1995 helped demonstrate the applicability of MCDA-based analysis to household energy supply systems. The model is popular among researchers. (Ehyaie and Bahadori, 2007; Jinturkar and Deshmukh, 2011; Trutnevyte et al., 2011; Ahammed and Azeem; 2013). Secondly, the authors reached an insightful conclusion that off-grid rooftop solar was the best alternative solution in areas where it is impossible financially and technically to extend the central grid.

A comparable study conducted by Pohekar and Ramachandran (2004), also in India, based on the PROMETHEE technique aimed at evaluating cooking devices, revealed notable differences with results and conclusions reached by Ramanathan and Ganesh (1994, 1995).

¹² Centralised grid; localised biogas, fuelwood, diesel and solar PV

Pohekar and Ramachandran (2004) found that the LPG stove was the most preferred device for cooking among low-income families in India, followed by the kerosene stove. The study points to the evolution of energy supply technologies. This condition implies that studies of this nature, including the current study, anchored on modified frameworks, should be conducted on an ongoing basis as new technologies emerge.

iii. Weaknesses

While the AHP and GP models applied are potent techniques for addressing decision problems involving multiple objectives, the models developed by the authors were limited to solving an exact deterministic issue, the assessment of off-grid systems for low-income communities. This limitation restricts the study's application to low-income households' electricity-producing technology. The energy supply decision dilemma has recently expanded beyond power supply.

iv. Lessons learnt for the pursuit of the present study

The study demonstrated the strengths of multi-objective energy techniques and combined studies to assess household energy supply options in a developing country. The study confirms findings from Chapter 2 of this study which revealed that despite rapid electrification in South Africa, the use of firewood and paraffin for meeting thermal requirements, notably cooking, remained prevalent and unchanged in rural and informal dwellings (Thom, 2000; Howells et al., 2006; Madubansi and Shackleton, 2006; Matinga and Annegarn, 2013; Stats SA, 2016; Stats SA, 2019). The studies reviewed were instrumental in the development of future-oriented energy access scenarios considered in the present study.

c. Stewart and Scott (1995), South Africa

The study adopted investigated strategic decision analysis in water resource planning in South Africa. The framework developed and applied allowed the extension of an a priori multi-objective water resource allocation problem to an MCDA problem.

i. Decision-maker involvement

The decision-makers comprised a panel of individuals drawn from the Department of Water Affairs and Forestry, and these were involved in the development of the model. The panel considered six criteria for evaluating five contrasting water resources policy scenarios. The panel was instrumental in establishing both alternatives and criteria and was involved in decision-making. Parameters used in the study were based on academic literature, the panel of experts and publications on water supply technologies.

ii. Strengths

Despite being an experiment, the research has been applied to real-world water resource planning in South Africa (Joubert et al., 1997; Joubert et al., 2003). “Decision conferencing,” “scenario-based policy analysis,” and “visual interactive sensitivity analysis” were all incorporated into the study. This prompted the current study to include decision conferencing (Phillips, 1988), scenario-based policy analysis, and graphic interactive sensitivity analysis. Given the parallels in stakeholders, albeit in different sectors, this adoption makes the study more relevant to the current study.

iii. Weaknesses

While the approach established proved effective for handling multi-objective choice issues, the authors’ models were confined to solving hypothetical policy recommendations. The analysis was based on an incompletely analysed policy alternative and a hypothetical implementation of the model established in the water resource planning domain. At the time of the study, these possibilities were not genuine government policy proposals. Nonetheless, the study framework techniques have been applied in several investigations, including the current one.

iv. Lessons learnt for the pursuit of the present study

Although used hypothetically in regional water resource planning, Stewart and Scot’s (1995) work gave significant insight to the current investigation. The research provided a larger framework for overcoming the challenges of using MCDA approaches in decision-making. The research also included a review of “policy scenarios.” As part of the approach, the current study borrowed the concept of “policy scenarios” and examined different scenarios (refer to Chapter 6 and Chapter 7).

d. Haralambopoulos and Polatidis (2003), Greece

In 2003, Haralambopoulos and Polatidis explored the application of an outranking technique to decision-making and policy formulation and evaluation in the public sector to address the problem. The study investigated the feasibility of investing in geothermal technology for electricity generation in Chios, Greece. The study recognises the challenge of investing in new energy technologies in an environment characterised by numerous players and conflicting priorities.

i. Decision-maker involvement

The decision-makers comprised a panel of individuals drawn from mass media and non-governmental organisations (NGOs) active in the region, investors involved in energy projects

and local authorities. These decision-makers were involved in the development of the model and case study application. The panel considered three quantitative and two qualitative criteria for evaluating four alternative geothermal resources policy scenarios. Parameters used in the study were based on academic literature, the panel of experts and publications on energy supply technologies. The panel was active in the decision-making process and was essential in formulating both alternatives and criteria.

ii. Strengths

MCDA, according to the authors, could be regarded as best practice for evaluating integrated renewable energy expenditures. Based on the investigation's prescripts, the normative decision-making framework helped demonstrate the applicability of MCDA methodologies in examining comparable energy technologies and problems (San Cristobal, 2011, 2012; Tsoutsos et al., 2009; Scott et al., 2012; Stein, 2013; Samanlioglu and Ayag (2017).

iii. Weaknesses

The study's fundamental flaw is due to the PROMETHEE technical constraints detailed in Section 3.3.4. The PROMETHEE approach, according to Pohekar and Ramachandran (2004), does not give a precise method for assigning weights. Furthermore, PROMETHEE methods, according to De Keyser and Peeters (1996), can only be used if the decision-maker can express their preference between two actions solely based on supplied criteria on a ratio scale. The need to evaluate several actions motivated the present study.

iv. Lessons learnt for the pursuit of the present study

Based on the investigation's prescripts, the normative decision-making framework helped demonstrate the applicability of MCDA methodologies in examining comparable energy technologies and problems.

e. Begić and Afgan (2007), Bosnia and Herzegovina

Begić and Afgan (2007) suggested that strategic energy planning requires robust multicriteria-based decision-making aids to prevent bias in the selection of sustainable energy supply technologies. The authors argued that most techniques for decision-making use single criterion assessment, which was considered problematic by the authors given the complexities associated with energy systems.

Against this background, the study evaluated the selection of eight energy supply options for an electricity utility company using both single criteria analysis and multiple criteria. The study employed an MCDA mathematical technique based on the synthesis of fuzzy sets. Studies

conducted earlier on the sustainability of energy supply options focused mainly on on-site selection (Mladineo et al., 1987; Skikos and Machias, 1992; Barda et al., 1990). Against this background, the study evaluated the selection of eight energy supply options for an electricity utility company using both single criteria analysis and multiple criteria. The study employed an MCDA mathematical technique based on the synthesis of fuzzy sets. Mladineo et al. (1987) applied the PROMETHEE technique and postulated that MCDA techniques provide a realistic solution to complex power plant site selection problems.

i. Decision-maker involvement

The authors considered four sustainability criteria for evaluating eight options for providing additional electric power capacity within the energy power system of Bosnia and Herzegovina. Given the technical and theoretical nature of the study, no decision-makers were involved in establishing the criteria for the evaluation of alternatives. Parameters used in the study were based on academic literature and publications on electricity supply technologies.

ii. Strengths

Results of the Begić and Afgan (2007) investigation demonstrated the severe deficiencies of single criteria analysis in the evaluation of complex energy problems. The authors claimed that single criteria analysis is not advised since it leads to subjectivity, which lowers decision quality.

The framework developed can work with limited information. The study has been empirically applied in the sustainability evaluation of sophisticated energy, mining, and forestry, where the information available is typically non-numeric, non-exact, and non-compete (Afgan and Carvalho, 2008; Jovanović and Afgan, 2009; Tsoutsos et al., 2009; Skobalj et al., 2017).

iii. Weaknesses

While the MCDA technique applied proved to be sufficient for addressing choice problems involving numerous objectives in the electricity, the authors' models were limited to handling an experimental problem and did not engage decision-makers.

iv. Lessons learnt for the pursuit of the present study

The study used single and multiple criterion analysis and found that sole criteria analysis is ineffective. As previously stated, real-world MCDA applications necessitate time, money, and human resources. Less complex options are still required, particularly for project screening. The goal of this study was to create a model that was less complicated but still useful - the

use of MCDA models in the current study assisted in the resolution of difficulties related to simplicity.

f. Cherni et al., (2007), Colombia

Poverty is particularly severe in remote rural areas of Colombia. The authors noted that policymakers omit renewable energy technologies in energy plans due to centralised decision-making in many developing countries such as Colombia. Furthermore, the study recognised the danger of endorsing renewable energy technologies as a cure-all solution for solving rural energy access problems without careful consideration of all the attributes. The authors posited that renewable energy technologies have unique challenges that need to be resolved to avoid failure at implementation. Ghosh et al. (2002) also reached a similar conclusion.

Cherni et al. (2007) postulated that there are several complexities associated with investing in rural energy supply infrastructure. For acceptance, decision-support systems must account for any given technology's financial, technical, social, environmental, and human aspects (Cherni et al. (2007)). The authors employed the GP technique (Yu, 1973; Zeleny, 1973; Yu and Zeleny, 1975) to evaluate energy portfolios for low-income communities in isolated rural areas in Colombia. The study results established that “while the use of new energy technology to promote sustainable rural livelihoods is necessary, a dynamic and comprehensive perspective must be employed to appreciate and factor in its many linkages.”

i. Decision-maker involvement

It was difficult to reach the secluded rural areas. Decision-makers and the community were represented by a panel of key stakeholders and local leaders. The case study application included these decision-makers. For the evaluation of eight alternative energy supply systems, the panel used both quantitative and qualitative criteria. The panel was involved in decision-making and was instrumental in formulating both options and criteria. The study's parameters were developed using academic literature, a panel, and publications on energy supply technology.

ii. Strengths

The study is beneficial for researchers working on energy planning in developing nations like South Africa, where some distant rural socio-economic and topographical characteristics are like those found in remote Colombian rural areas. Similar reviews in Manantiales, Cuba (Cherni and Hill, 2009) and Jambalo, Colombia (Cherni and Hill, 2009) were based on the paradigm developed by Cherni et al. (2007). (Heano et al., 2012). Heano et al. (2012) built on previous work by Cherni et al. (2007) by including robustness analysis. The Cherni et al.

(2007) model has also been empirically tested in Rwanda, Tanzania, and Malawi to analyse energy supply choices in remote rural locations (Barry et al., 2011).

Silva and Nakata (2009) used the GP approach to evaluate renewable energy solutions for rural electrification in Colombian communities. According to Silva and Nakata (2009), traditional biomass paired with renewable energy sources outperformed other options in terms of carbon emission reductions and job generation. Ceron et al. (2017) used the fuzzy logic theory in a comparative investigation in Colombia and came to a different conclusion. In comparison to Silva and Nakata (2009), the study findings suggested that a hybrid generating mix of 96% diesel generators and 4% wind turbines were the optimal energy supply choice for the area. The Colombian government began deploying renewable energy systems based on microgrids in 2019 to enhance access to power for isolated and disadvantaged communities (Bueno-López et al., 2019).

iii. Weaknesses

The study by Cherni et al. (2007) had one major flaw: the framework was biased towards renewable energy technology, even though the technique was designed for poor and isolated rural people. The research was similarly limited to identifying the best option but did not provide additional guidance during the decision-making process.

iv. Lessons learnt for the pursuit of the present study

Cherni et al. (2007) produced a ground-breaking study that was especially valuable for energy planners in developing countries like South Africa, where several distant rural socioeconomic and geographic traits are like those found in remote Colombian rural areas. The study's purpose was to develop a framework to assist government decision-makers. The current study developed a model that demonstrates the benefits of the multi-objective energy combination technique in a developing country.

g. Lhendup, (2008), Bhutan

Bhutan is a low population country with a scattered pattern of settlements and rugged terrain. Connecting each household requires significant capital, which may not be feasible given the low energy demand and inability to charge cost-reflective tariffs. Most homes in rural Bhutan rely on subsistence farming (Lhendup, (2008). Bhutan is classified by the World Bank as one of the world's least developed and lower-middle-income countries. The country's hydroelectric potential is grossly underutilized. Hydroelectricity is a net exporter for the country (World Bank, 2016).

i. Decision-maker involvement

Given the technical and theoretical nature of the study, no decision-makers were involved in establishing the criteria for the evaluation of alternatives. The authors considered the three qualitative criteria (technical features, government regulations and social aspects) to evaluate of energy supply technologies options. Parameters used in the stud were based on academic literature and publications on electricity supply technologies.

ii. Strengths

A modest Microsoft Excel-based weighting MCDA technique was employed to evaluate distributed electricity generation technologies in rural Bhutan. The study found that it was uneconomic for the government to insist on extending the central grid in the era of renewable energy technologies. However, a related study conducted in the Brazilian Amazon by Nerini et al. (2014) employing a simple weighting MCDA technique reached a different conclusion. Nerini et al. (2014) established that renewable and hybrid diesel-based energy systems present several advantages for application in isolated areas in the Amazon region of Brazil.

iii. Weaknesses

In the studies, just a few options were investigated. Lhendup's (2008) research was also heavily weighted in favour of renewable energy technologies. The study's options were limited to rural electrification, ignoring other forms of energy for energy supply, as previously noted in this section (Brand and Missaoui, 2014; Cherni et al., 2000; Cherni and Hill, 2009; Silva and Nakata, 2009; Heano et al., 2012; Blanco et al., 2017), reducing the paper's efficacy for wide-ranging energy technology investigation. Because, as claimed by Matinga and Annegarn, even with affordable technologies, communities may continue to use other forms of energy based on religious and spiritual beliefs, the study by Lhendup, (2008) could incorporate ethnographic criteria such as socio-cultural and expand the options menu to non-renewable energy technologies (2013).

iv. Lessons learnt for the pursuit of the present study

The contributions of Lhendup (2008) and Nerini et al. (2014) to this study were threefold. To begin with, the assessment was crucial in identifying potential rural energy supply technologies. For the current study, a variety of options were investigated with the panel of experts and included in the portfolios that were developed. Second, the survey showed that rural electrification efforts in many nations rely on connecting families to the national grid. These are the topics of the present investigation. Hughes et al. (2017) identified comparable locations, which are described in section 2. The research debunked the myth that grid

electricity is the cure for all energy access problems. Finally, the implementation of a simple weighted MCDA technique based on Microsoft Excel proved that MCDA research may be commissioned utilizing low-cost, easy-to-use software.

h. Buchholz et al, (2009), Uganda

The study evaluated the sustainability of bioenergy systems in a remote rural village near Kasonga in south-western Uganda using four different MCDA platforms developed by Munda (2006): Super Decisions, DecideIT, Decision Lab, and Novel Approach to Imprecise Assessment and Decision Environments (NAIADE). Super Decisions applied the AHP technique; Decision Lab used the PROMETHEE II technique, DecideIT software employed the DELTA technique, based on the MAUT technique and the NAIADE falls under the outranking school.

i. Decision-maker involvement

It was thought that reaching out to the entire village of around 500 people would be difficult. Decision-makers and the community were represented by a panel of nine important stakeholders and local leaders from Kasonga Trading Centre in Uganda, the case study area. The evaluation included eight of the decision-makers. Participants included representatives from the government, non-governmental organizations, and women's organizations.

For the examination of alternative bioenergy technologies, the panel used both quantitative and qualitative criteria. The panel was involved throughout the decision-making process and was essential in creating both alternatives and criteria, criteria weights, and scenario performance. Academic literature, the panel, and articles on bioenergy supply technologies were used to develop the study's parameters.

ii. Strengths

According to the authors of this study, different MCDA methodologies may produce different results, and social criteria, not prices, are critical in making bioelectricity systems feasible for deployment in a Ugandan rural community. According to the findings, MCDA can help with stakeholder integration and communication of complicated decisions. The use of several MCDA strategies to tackle the portfolio selection problem was another strength of Buchholz's (2009) study. The combination compensated for any deficiencies in any one technique.

iii. Weaknesses

The study looked at only a few possibilities and only one technology type. The study's options are limited to a single technology (bioenergy systems), neglecting other kinds of energy, diminishing the paper's usefulness for a broad review of energy technology.

iv. Lessons learnt for the pursuit of the present study

The contribution and significance of this study to science lay in applying various MCDA techniques to a specific problem and the realization that, regardless of the MCDA technique used, the study was useful in evaluating bio-energy projects in isolated and impoverished rural areas communities using social criteria. The study also aided the current study's author and a panel of experts in organizing the problem, identifying the least reliable and/or most uncertain components in rural electricity delivery, and incorporating stakeholders into the decision-making process.

i. Van Blommestein and Daim, (2013), South Africa

The power shortages attributed to demand exceeding supply experienced in the later months of 2007 in South Africa prompted the need to consider investing in energy efficiency technologies. In 2007, Eskom introduced incentives to encourage the implementation of energy-efficient technologies by consumers. Van Blommestein and Daim (2013) postulated that the complexity of investing in energy-efficient technologies required a decision model that would incorporate preferences that a consumer considers when purchasing energy-saving technologies. The study employed a hierarchical decision model based on the AHP framework.

i. Decision-maker involvement

Given the technical and theoretical nature of the study, no decision-makers were involved in establishing the criteria for the evaluation of alternatives. The authors considered performance, environmental, economic, service and support and convenience criteria for the evaluation of energy-consuming devices. Parameters used in the study were based on academic literature, inputs from consumers and publications on electrical device technologies.

ii. Strengths

While the study was limited to the evaluation of energy-efficient devices, the paper was significant to the energy technology evaluation and strategic energy planning and decision-making in South Africa. The study results offered a solid foundation and valuable insights into the applicability of MCDA techniques to energy technology analysis and energy planning in the country.

iii. Weaknesses

The study's focus was limited to eleven power end-uses, limiting its use for broader energy technology analysis. One option to overcome this limitation was to expand the list of stakeholders involved in the problem and decision. The technical limits and applicability of the AHP, as noted by Velasquez and Hester (2013) and explored in Section 3.3.5, was another negative of this study. These issues and limitations drove the development and implementation of the framework employed in this study.

iv. Lessons learnt for the pursuit of the present study

The study's focus on energy technology evaluation in South Africa was the study's contribution and significance to science. The current investigation uncovered important information about appropriate technologies, energy-consuming appliances, and gadgets for implementation in South Africa.

j. Stein, (2013), US

Bordering on the studies by Jones et al. (1990) and Haralambopoulos and Polatidis (2003), Stein (2013) assessed the feasibility of renewable energy and non-renewable conventional technologies using the value function technique in the US. The investigation supported the argument posited by Jones et al. (1990) and later by (Akash et al., 1998; Chatzimouratidis and Pilavachi, 2009) that renewable energy sources provide more benefits to society than non-renewable options.

In the same way, Burton and Hubacek (2007) applied an MCDA technique combined with a CBA approach to energy technologies evaluation. They concluded that small-scale schemes are the most effective based on the criteria used. The same phenomenon was also observed in Finland by Alanne et al. (2007). The studies suggested that micro energy generation technologies are a reasonable alternative to traditional systems if one is to consider the environment.

i. Decision-maker involvement

Given the technical and academic nature of the study, no decision-makers were involved in establishing the indicators for the evaluation of power generation alternatives. The authors considered four criteria clusters: financial, technical, environmental and socio-economic-political. Parameters used in the study were based on academic literature and publications on electricity generation technologies.

ii. Strengths

The created decision-making framework demonstrated the utility of MCDA techniques in comparing similar energy-producing systems. The study's outcomes back up earlier claims made by Jones et al. (1990), bolstering the commercial case for using MCDA-based methodologies to solve energy planning challenges.

iii. Weaknesses

The study's focus was limited to a road review of electricity generation technologies limiting its applicability to a broader investigation of energy technologies. As previously mentioned and comparable to studies based on the AHP technique, an additional downside of this study was the technical limits and applicability of the AHP procedure stated in Section 3.3.5.

iv. Lessons learnt for the pursuit of the present study

The decision-making framework developed demonstrated the utility of MCDA techniques in comparing similar energy-producing systems. While the methods utilized differed, the current research borrowed several concepts and ideas from constructing a typical energy problem, articulating group decisions, and the importance of public engagement in inclusive decision-making.

k. Blanco et al., (2017), Paraguay

Paraguay has enormous renewable energy potential. The state already has an existing large hydropower surplus. However, electricity consumption in the country is the lowest in the Latin American region (World Bank, 2017). The low rates of electricity usage have endangered the economic development potential of the country (Ibid). According to the World Bank (2017), the answer to unravelling economic progress lies in developing an energy transition policy framework anchored on maximising the country's energy resources (Ibid). The study developed a decision-support model to confront the decision-making problem faced by the government of Paraguay.

i. Decision-maker involvement

Four policy options were considered based on economic, technical, social, environmental and political criteria. The options were generated based on the results of consultation among stakeholders. A panel comprised of 80 local stakeholders was established and consulted for preferences, weighting the preferences of the criteria and sub-criteria. The five criteria were categorized according to their degree of importance based on the results of a survey conducted among the stakeholders. The surveys were used to collect information on their cardinal preferences of the criteria on a scale from 1 to 9.

ii. Strengths

Given the high levels of social inequality, economic issues and climate change and environmental challenges, the study highlighted the appropriateness of MCDA in emerging countries faced with the necessity to balance opposing demands.

iii. Weaknesses

Because of the technical limitations described in Section 3.3.5, the study methodology based primarily on the AHP technique weakens the investigation. Furthermore, the scope of the study was restricted to the evaluation of hydroelectricity power generation systems, limiting its application to a broader investigation of energy technology.

iv. Lessons learnt for the pursuit of the present study

The developed model is empirically applicable to various developing and underdeveloped nations with energy access problems, such as the Democratic Republic of Congo (DRC) and Mozambique and South Africa, where energy availability in some areas continues to hinder development.

The study established the appropriateness of MCDA in emerging markets; the authors claim that MCDA approaches could aid decision-making processes by offering a more comprehensive and multilateral perspective, allowing for a more balanced approach to energy policymaking. The current study used concepts and ideas from previous research to create a hierarchical framework that includes an objective, criteria, sub-criteria, sub-sub-criteria, and alternatives.

4.5 Major topical issues in existing studies

4.5.1 Application of MCDA techniques in the energy sector

The summaries of MCDA empirical applications discussed in the previous section and summarised in Table 6 validated the diverse application of MCDA techniques to energy resource planning problems. The literature review exercise revealed that the energy infrastructure planning problem and decision-making using MCDA techniques cover a broad range of application areas in many countries. Table 6 summarises the first empirical studies examining national strategic energy investment planning and policies. These studies confronted the challenges of choosing between policy options favouring different energy technologies for electricity generation in the US, Germany, Finland, Paraguay and Tunisia. MCDA was relatively unknown in the energy policy field when these studies were conducted. There had been no known attempts to apply the science in energy policy or any other public policy issues.

Earlier research by Buehring et al. (1978), Keeney et al. (1987), and Jones et al. (1990) investigated the use of value functions to aid decision-makers in evaluating various policies and concluded that using frameworks developed in the public sector could be beneficial. The use of the AHP technique by Hämäläinen (1988) and Blanco et al. (2017) prompted the desire to understand energy policies better. On the other hand, brand and Missaoui (2014) analysed power generation scenarios for a developing country to help policymakers better grasp the complexities of energy policy planning in developing and undeveloped countries.

The second band of empirical research applied MCDA techniques related to the evaluation of energy supply technologies. Studies by Golab et al. (1981), Haralambopoulos and Polatidis (2003) and Stein (2013) explored the feasibility of new energy technologies and the selection of energy supply technologies. These studies are still relevant today.

The empirical investigations reviewed recognised the challenges associated with investing in new energy technologies in an environment characterised by constantly evolving technologies, constrained national budgets, numerous players and conflicting priorities. The basis for empirical investigations by Burton and Hubacek (2007) and Alanne et al. (2007) was enquiring about the environmental feasibility of micro energy generation technologies with large scale schemes.

The third set of studies focused on assessing alternative power systems with a greater focus on sustainability. These studies include work by Begić and Afgan (2007), Doukas et al. (2007)

and Streimikiene et al. (2012) where the primary motivating factor was the assessment of the sustainability of current and future sustainable energy supply technologies. Strantzali et al. (2017)'s study added transparency to the process of selecting the optimum sustainable fuel mix for electricity generation and energy system growth.

The fourth set of studies covered the evaluation of remote rural and low-income household energy supply options. Several studies in this cluster featured a familiar researcher, Dr Judith Cherni of Imperial College London and employed the sustainable rural energy decision-support system (SUREDSS) technique developed. Ramanathan and Ganesh (1994); Cherni et al. (2007); Heano et al. (2012); Silva and Nakata (2009); Ceron et al. (2017) all focused on evaluation and selection of electricity generating and bioenergy alternatives suitable for isolated and low-income communities.

The fifth group of empirical investigations covered the assessment of energy efficiency and building energy management systems. Blondeau et al. (2002), Roulet et al. (2002), and Rutman et al. (2005) examined the selection, ranking and prioritisation of building energy management systems considering comfort, air quality and energy consumption. With the exception of Van Blommestein and Daim (2013), who looked at energy-saving devices. Similar research by Kaklauskas et al. (2005), Martinaitis et al., (2007), Jaggs and Palmer (2000), and Caccavelli and Gugerli (2002) was driven by the necessity to evaluate building rehabilitation and energy efficiency improvement initiatives.

The objectives of the studies reviewed in this section appear to address some of the pressing energy planning and decision-making problems and demonstrate the suitability and benefits of MCDA techniques in confronting energy infrastructure investment decisions. The objectives of these studies resonated with the objectives of the current study. These studies provided a useful guide on the formulation of the objectives of the current investigation. In the many studies reviewed, however, a common theme emerged, the objective was not to examine the broad energy supply problem through MCDA. Somewhat, many studies were limited to the evaluation of electrification alternatives as opposed to confronting the more general objective of energy supply alternatives.

Energy supply choices for a country range from traditional biomass options such as firewood for remote areas, LPG, electricity-based supply, energy efficiency and energy storage. Chapter 2 of this study revealed that many households continue to use firewood for cooking despite electrification. The same is true in many parts of the world based on empirical literature reviewed.

The objectives of many of the studies reviewed provided a narrower definition of the energy problem and the application of MCDA techniques to energy planning and decision-making. No single investigation exists that evaluates low-income household energy supply options outside electrification. In other words, this indicates a knowledge gap in research. The present study addressed this identified research gap by expanding the energy supply problem definition to include all energy applications for poor communities. The concerns and limitations raised in this chapter motivated the design of a novel MCDA framework that combines technical and non-technical criteria for the development of rural energy supply infrastructure among low-income households to promote effective and sustainable energy solutions by improving decision-making processes.

4.5.2 MCDA techniques applied

A key observation from the literature review was that the application of MCDA on its own was often subjective. At the same time, it also established that it was mathematically challenging to find Pareto-optimal solutions while at the same time accounting for multiple objectives in combinatorial problems. This limitation hamstrung several studies reviewed. The empirical review observed that the latest trend in decision theory was the combination of two or more techniques to make up for shortcomings in any single approach (Stewart and Scott, 1995; Buchholz, 2009; Streimikiene et al., 2012; Rojas-Zerpa and Yusta, 2015). This was accomplished by using a staged problem structuring method based on the Mintzberg et al. (1976) general model for problem structuring (Stewart and Scott, 1995). Mintzberg et al. (1976) argued in "*The structure of 'unstructured' decision processes*" that strategic decisions are "novel, complex, and open-ended, with decisions made not so much under uncertainty as within a continuous state of ambiguity, where almost nothing is given or easily determined".

Owing to the research papers discussed in this chapter, the author of this study was able to address the problem of energy access among low-income households. As noted in 3.1, the multifaceted character of decisions demands some conceptual framework. By applying the Mintzberg et al. (1976) general problem structure model to the current inquiry, it was possible to extend the multi-objective GP optimization and the MAVT technique to an MCDA issue. In public energy planning, a strategy combining GP and value function techniques, based on Mintzberg et al. (1976) problem structuring postulate, has yet to be applied.

4.6 Chapter conclusion

This chapter reviewed existing research in order to provide the empirical basis for the adoption of MCDA techniques to the energy planning problem and decision-making. According to the

findings, there is a substantial body of academic research that supports the employment of MCDA techniques to solve the energy supply problem. The current research studies are insufficient to answer the current study challenge, as detailed in this chapter.

This chapter also established that existing studies using MCDA approaches to address energy access and planning problems primarily focused on solving the electricity supply problem. Studies that discussed energy supply problems for low-income and isolated rural settlements concluded that electrification underpinned by renewable energy technologies is the panacea for confronting the rural and low-income household energy problem.

The empirical evidence addressed in this chapter and Chapter 2's assessment of the energy supply situation in rural and informal settlements in South Africa uncovers some interesting phenomena that run counter to the belief in grid electrification. Many studies have overlooked conventional and non-electricity-based energy supply techniques that, in some way, meet the thermal, lighting, and pumping needs of low-income people even when they lack connection to the electric grid. As a result, the current study contends that energy policy analysis should be based on a thorough examination of the complete energy system value chain.

According to the literature review findings in this chapter, no single multi-objective or MCDA technique is superior. According to empirical evidence, the employment of two or more strategies to compensate for deficiencies in a single strategy is the newest trend in decision theory. The nature and kind of the problem, the number of options available, the number of stakeholders involved, the type and availability of data, and the criteria used all impact the decision. As a result, problem-specific frameworks were created, such as the one used in this study. The following chapter describes a novel technique for selecting a portfolio of energy supply technologies.

CHAPTER 5

A FRAMEWORK FOR MULTI-CRITERIA DECISION ANALYSIS IN RURAL ENERGY SUPPLY PLANNING

5.0 Chapter introduction

This chapter introduces a new decision-making framework for selecting a portfolio of energy supply technologies for low-income households. The framework developed aims to guide decision analysts and decision-makers faced with an energy access problem. While many MCDA techniques exist for strategic decision-making, the author is unaware of any expressly created public policy frameworks to handle the energy access challenge in a developing country. Also, according to Archer and Ghasemzadeh (1999), using a single framework for various situations and expecting quality decisions is counterintuitive. Each problem has its unique peculiarities. In light of this, a unique MCDA-based strategy was created to assist decision-makers dealing with strategic energy planning challenges. The methodology developed is intended to aid in the assessment of various scenarios for coping with an unstructured energy planning challenge among low-income households.

5.1 Energy planning in South Africa

In most decision problems, including energy planning, several conflicting objectives must be considered, given multiple actors with diverse opinions and interests. In such an environment, preferences and considerations differ, making project planning, approval and implementation problematic. The squabbling over nuclear power, renewable energy and the rejection by some rural communities of the non-grid electrification programme presents a classic example in South Africa. It was accordingly imperative that an appraisal framework that accounts for both monetary and non-monetary impacts needed to be developed. The technique should allow for broader stakeholder participation and communicate the complexity and uncertainties associated with decisions. Also, the approach must result in the selection of coherently assembled development plans from collections of projects.

MCDA has been recognised as one of the leading techniques for overcoming some of the shortcomings of single criteria and one-dimensional approaches in infrastructure development and public-sector strategic planning (Pohekar and Ramachandran, 2004; Munda, 2005; Løken, 2007; Wang et al., 2009). According to Belton and Stewart (2002), MCDA is an integrated evaluation criterion and decision-support system suitable for dealing with complex and multifaceted problems. Conflicting perspectives and objectives, multi-interests and high

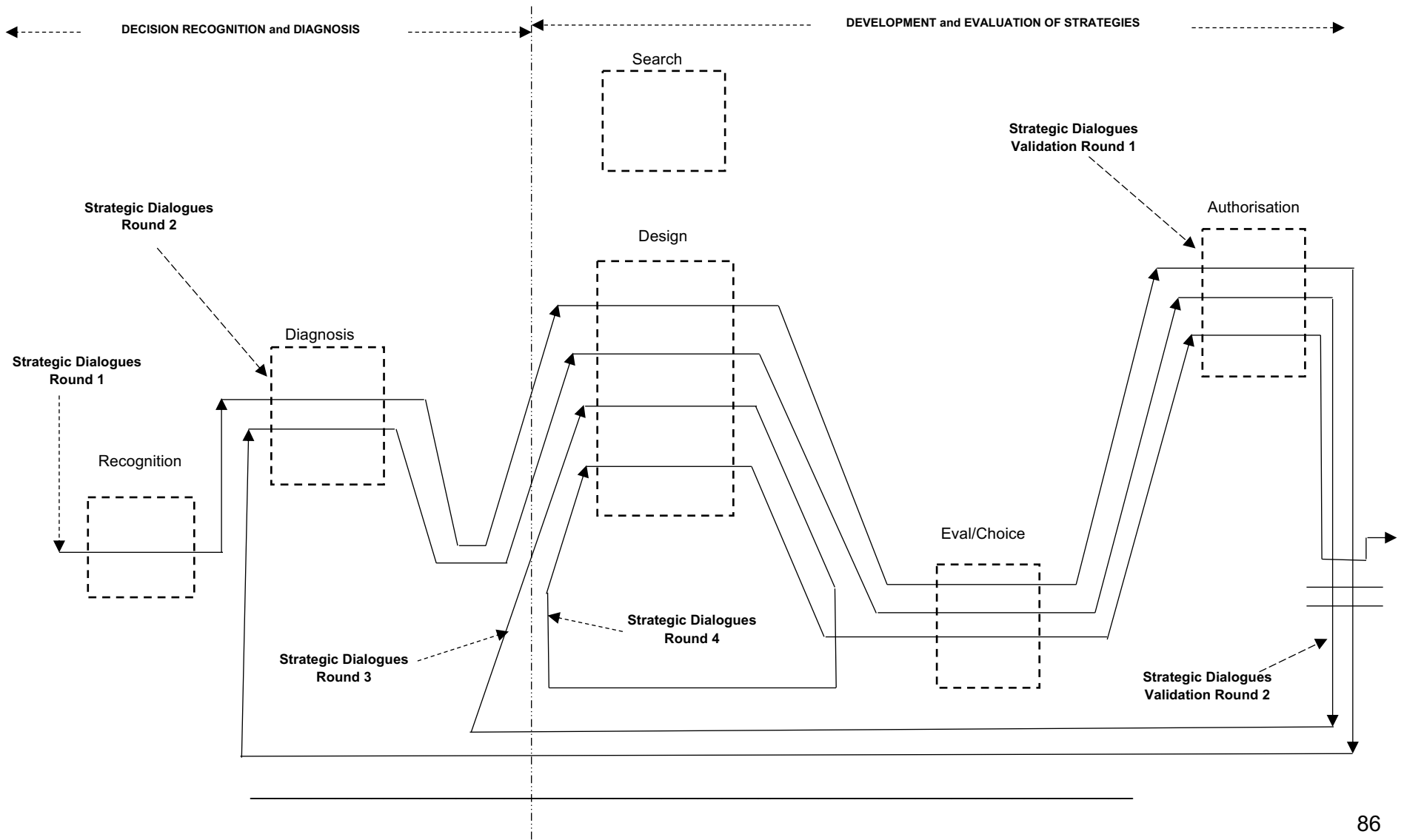
levels of uncertainty characterise these problems. Attempts to employ existing MCDA frameworks to address the energy access problem in South Africa proved futile. The study framework borrows concepts from the model developed by Mintzberg et al. (1976) and the MDCA process (Belton and Stewart, 2002; Rosenhead and Mingers, 2004). Figure 17 presents a schematic representation of the overall portfolio-based energy policy planning framework developed for the study.

The first stage takes the form of a series of strategic dialogues with a panel comprising energy sector industry experts from various interest groups (See Figure 17). The strategic dialogues should be conducted with a commitment to confidentiality and ethics. Given this vast pool of stakeholders to the problems, budgetary and time constraints, it is not feasible to solicit the views of all stakeholders to the problem. Therefore, the study need not single out any individual. The developed framework suggests that the decision analyst only needs to select a smaller number of representatives, including those representing the end-user whose opinions could be considered representative of the broader stakeholders to the problem.

The framework developed proposes the snowball sampling technique for broader stakeholder identification and mapping process. The justification for using the snowball and purposive sampling techniques was that experts on the subject were unknown and rare, and it was difficult to choose subjects to assemble as samples for research. A suggested approach in establishing a panel of experts is that the decision analyst would need to conduct a stakeholder analysis to identify key interest groups and main stakeholders to the problem.

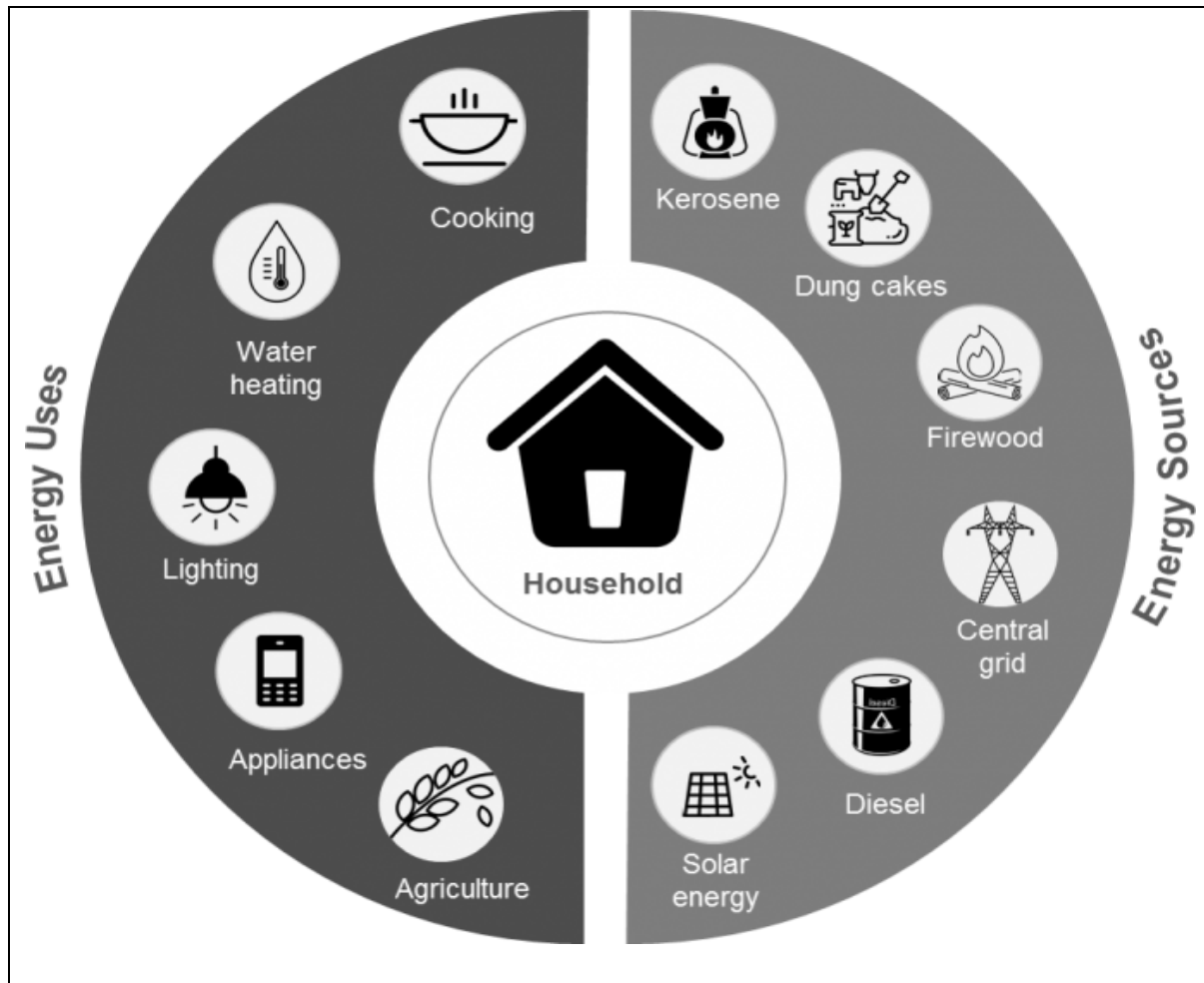
The decision analyst would need to identify a database of stakeholders comprised of key individuals representing different organisations. The key stakeholders to the problem should be identified as individuals and organisations involved in the energy sector or a different sector in cases where the framework developed is applied in a different sector. Once established, the panel is requested to identify and define all possible scenarios from their perspectives. The identified panel members ought to be individuals and organisations with vested interests in its outcome from diverse backgrounds. At a bare minimum, the experts should be drawn from the industry, academia, government, elected representatives, community leaders, the private sector, and non-governmental organisations involved in the model's development and application. Emphasis is placed on generating as many portfolios as possible. An iterative process is then adopted to refine and redefine the portfolios until a consensus is reached.

Figure 17: Schematic representation of the overall portfolio-based low-income household energy policy planning framework



In the context of the framework developed, a rural energy portfolio was defined as a set of energy supply technologies (sources) for meeting the energy needs of families (uses). Figure 18 represents a typical energy portfolio for a rural family.

Figure 18: Illustrative energy portfolio for a rural household



Source: Agarwal et al. (2018)

5.2 Identifying and defining policy portfolios and appraisal

A fundamental guiding principle in scenario-based policy planning is that alternatives to a problem cannot be deduced from an existing list without observed facts. Put another way, no predefined options exist based on expert or theoretical arguments. In essence, therefore, scenario planning provides the means for the initial screening required to generate alternatives. In the end, the selection should result in the development of generally acceptable portfolios.

In the first iteration, loosely defined portfolios are assembled from various potentially feasible and infeasible policy options. This collection represents the first set of portfolios. The procedure for developing the initial portfolios is discussed in the next paragraph. These base portfolios are generally lightly defined and are further clarified during the implementation phases of the framework developed. Finer details and variations are addressed as strategic dialogue members thinking evolves and converges over time. The decision analyst's role at this stage is limited to guiding the panel members to generate as many alternatives as possible.

The already mentioned panel of experts is entrusted with identifying policy components relevant to energy planning actions. The PESTEL analysis is used to identify the key factors, trends, and uncertainties that may have an impact on the strategy. These policy elements serve as the foundation for identifying energy policy concerns and, ultimately, developing possible portfolios. System sizing, availability, dispatchability, land, water usage, carbon emission reductions, investment, and lifespan costs are all common concerns. At this point, it is possible to identify all viable possibilities, which are then methodically recorded.

A significant problem with the approach detailed above is the degree to which one can generate options. There is generally a limit to the maximum number of portfolios ranging between five and ten portfolios at a time (Miller, 1956). A second main limitation of the procedure is the time and financial resources required to complete the procedure discussed above. It can take between a year to two years to conduct a comprehensive screening of base options.

Given the financial and time constraints, 12 months is proposed for the framework in this framework, but the period can be longer. Data collection and modelling of the identified elements are also conducted in this phase. The base and secondary options are tabled for discussion with a panel of experts. Detailed steps about this procedure for developing base and secondary portfolios are discussed in Chapter 6 and Chapter 7.

5.3 Decision recognition and diagnosis

The framework developed combines two multi-objective optimisation techniques to generate energy portfolios of action for a community. These two techniques are the GP and the MAVT technique (Refer to Section 3.3.2 and Section 3.3.5 for definitions). This combination allows the extension of the GP technique to a MAVT technique. The two procedures are discussed

in the next section. The first section focuses on GP technique and the second section addresses the MAVT technique.

5.3.1 Selecting portfolios of action: goal programming

In this first iteration, portfolios are developed using the GP technique. As discussed in Section 3.3.2, the GP technique has been applied to the evaluation of energy access problems of a combinatorial nature (Ramanathan and Ganesh, 1994; 1995). Two elements must exist for GP evaluation, namely goals and constraints. The energy access problem qualifies for GP, given different stakeholders' different perspectives and goals that can be translated to objectives and constraints. A goal can be expressed as a constraint on the goal value expression plus or minus a deviation variable set which is equal to the desired goal level.

One of the key goals of the 17 wide-ranging SDGs, SDG seven, is “*ensuring access to affordable, reliable and sustainable and modern energy*”. Financial constraints, however, hamper investments in new and clean technologies to achieve considerable reductions in carbon emissions. Given the financial constraints, standard GP decision variables in the energy access problem include lifecycle costs, carbon emissions, thermal efficiency, time and capacity factors. Other constraints include limitations related to the time available for maintaining systems. Information related to the decision variables is often found in several national plans and published case studies.

GP allows decision analysts and decision-makers to investigate the role that different energy access strategies can play in national efforts to reduce carbon emissions at the same time meeting the desired outcomes. The identification of feasible alternatives can only be achieved if the pool from which they are drawn is adequately diversified. The objectives are derived from the expert panel outlined in Section 5.1.

The framework developed employed the augmented Chebychev approach (Wierzbicki, 1980, 1999). Under the model developed, standard linear programming was extended into the augmented Chebychev GP form for the energy planning problem. While the Chebyshev formulation is nondifferentiable and the formulation used is differentiable, the model was optimized using an LP framework that does not use derivatives. The LP framework is useful in solving the problem.

In the energy planning problem, the *minimisation* of z_k objectives is desired. The target, therefore, is to *minimize* the undesirable d_k^+ *deviation variables* with d_k^- playing no

substantial role. We therefore first suppressed the superscripts on the d_k^+ deviational variables and just wrote d_k with deviational constraints as:

$$z_k - d_k^+ \leq g_k \quad \text{Equation 3}$$

for $k = 1, \dots, K$.

z represents the objective, k criteria/objectives which may be scenario related, n = number of technologies considered. The augmented Chebychev GP formulation designed for the study, thus, sought to minimize $\max_{k=1}^n w_k d_k + \epsilon \sum_{k=1}^n w_k d_k$ for $\epsilon > 0$. As discussed above, for the study, a new D variable was introduced to deal with non-linearity with an additional constraint now formulated as:

$$D \geq w_k d_k \quad \text{for } k = 1, \dots, K. \quad \text{Equation 4}$$

a) Decision variables

In the model developed, different energy supply options (labelled Y) are to be considered for a representative community and to be deployed to form an energy mix in GJ (labelled $j = 1, \dots, n$). The decision variables for the model are thus defined as:

Y_j : provided (installed) capacity in GJ for technology j ($j = 1, \dots, n$)

X_{ijk} : quantity of installed technology j allocated to serving energy needs of six different uses i ($i = 1, \dots, n$) under conditions of three different scenarios k ($k = 1, \dots, n$).

The model developed considers climate change scenarios and these scenarios should be obtained from the strategic dialogues. The scenarios are based on a year in future labelled $t=\alpha$ with t representing time and α representing the selected year.

b) Constraints

The model developed for this study incorporated hard constraints based on the estimated household energy requirements for satisfying the basic needs discussed above. Two classes of hard constraints are thus defined as:

Capacity constraint: $\sum_i X_{ijk} \leq Y_j$ for all j and for each scenario k .

Demand constraint: $\sum_j X_{ijk} \geq \text{demand for use } i \text{ under scenario } k$ for all i and k . X_{ijk} denotes GJ of usable power for use i under scenario k delivered by an allocation of 1 GJ of installed capacity of technology j to this usage. In some cases, this parameter had a value 0 (not

appropriate), in many cases it may be 1, but represent efficiency in other cases (e.g., wind and solar power under certain conditions).

c) Objectives

Using the goal programming formulation, the analysts obtain the decision-makers desirable levels of performance, known as goals (g_k) for each objective, k ($k = 1, \dots, K$). In obtaining any feasible solution, non-negative deviational variables are introduced (d_k^+ and d_k^-). At least one of the deviational variables should be zero, such that $z_k + d_k^- - d_k^+ = g_k$ with z representing objectives k representing criteria/objectives which may be scenario related. The minus and the plus superscripts indicate whether a goal is to be minimised, over, or underachievement of the goal priority

The final objective function for the linear programming procedure to implement the augmented Chebychev GP metric for the energy access problem with the new D can thus be formulated as:

$$z_1 = \sum_{j=1}^n Y_j K_j \quad \text{Equation 5}$$

$$z_{2k} = \sum_i \sum_j X_{ijk} R_{ijk} \quad \text{Equation 6}$$

$$z_{3k} = \sum_i \sum_j X_{ijk} D_{ijk} \quad \text{Equation 7}$$

$$z_{4k} = \sum_i \sum_j X_{ijk} E_{ijk} \quad \text{Equation 8}$$

$$\text{Minimise } D + \varepsilon \sum_{k=1}^n w_k d_k \quad \text{Equation 9}$$

for $k = 1, \dots, K$.

Subject to the following constraints:

Capacity constraint: $\sum_i X_{ijk} \leq Y_j$ for all j and for each scenario k .

Demand constraint: $\sum_j X_{ijk} \geq \text{demand for use } i \text{ under scenario } k$ for all i and k .

The epsilon variant, ε , is a moderately small positive number greater than 0 (between 0.02 or 0.10). The assumed ε , ought to be small enough not to substantially affect the optimal value of the z_k , but large enough to ensure a Pareto optimality solution. As discussed in Section 3.3.2, the GP technique is popular in MCDA because of its simplicity. Finding optimal solutions

using the GP technique is straightforward to implement and has been universally and successfully implemented elsewhere.

5.4 Group decision-support for energy policy evaluation

The GP procedure's portfolio of actions should be presented to a panel of specialists for evaluation from various perspectives. In the framework developed, the portfolio of actions is evaluated to check for synergies, inconsistencies and apparent conflicts. In the case of energy planning, one of the main areas of contention is the need to balance carbon emission reduction goals and the least cost technology options. This disconnect is because most renewable energy technology options are generally more expensive than fossil-based energy generation technologies from a capital cost perspective. Besides, some of these technologies are usually not popular with rural communities, given the economic status associated with grid-based electricity. As observed in Chapter 2, traditional firewood is generally preferred by users despite the health hazards associated with such energy access options. Consensus among participants must be established before embarking on the next stage. The primary goal of applying standard MCDA techniques is to formulate preferences and communicate these preferences to different interest groups.

5.4.1 Model for evaluating alternatives

The additive model, based on the MAVT technique's foundations, is used in the framework designed to evaluate alternatives (Section 3.2.5). The MAVT technique is useful for evaluating problems with a restricted number of options that must be weighed against competing goals (Belton and Stewart, 2002). As discussed in the preceding chapter, Joseph et al. (2009) and Carwardine et al. (2012) advocate adopting explicit methods to avoid the mathematical difficulties that implicit methods present. The MAVT technique allows a weak performance of one criterion to be compensated by an excellent performance of another criterion, i.e., the good criteria totally balance out the negative criteria..

5.4.2 Sensitivity and scenario analysis

Phillips (1984) and Rehman and Romero (1993) endorsed using sensitivity analysis to test the robustness of a model and the results obtained. A detailed sensitivity analysis should follow the procedure discussed above. Sensitivity analysis stress tests the impact of weights on the final ranking of the alternatives until censuses have been reached, i.e., the final scores are a fair representation of a relatively homogenous interest. If no consensus emerges, the supposedly homogeneous group should be further divided into two different interest groups.

The framework developed employs the V.I.S.A groupware to conduct sensitivity analysis. (See Appendix D for a practical guide for using of the V.I.S.A software). Sensitivity analysis should generate a preference ordering along a defined scale for each major interested group. Under the current framework, the procedure for identifying scenarios is achieved through strategic dialogues with a panel of energy industry experts.

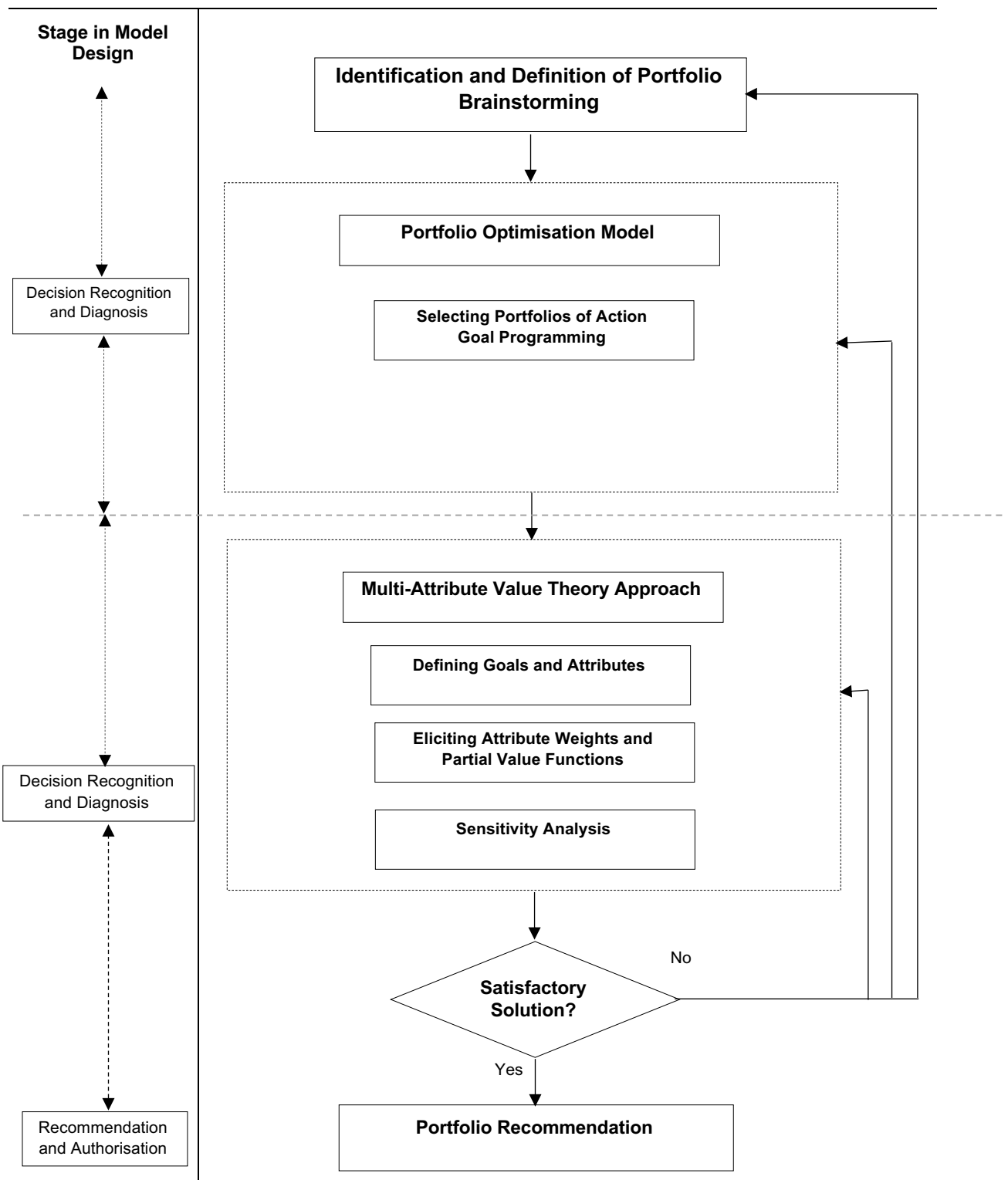
5.5 Portfolio-based policy planning framework

The author explains the approach that drives the development of an MCDA issue structuring framework in the preceding section. The resulting problem structuring framework is shown in Figure 19. The established framework is based on Mintzberg et al. (1976) problem structuring paradigm. It follows the processes outlined in Figure 17, namely decision recognition and diagnosis, development and evaluation of alternatives, and recommendation and authorization. The first stage is to develop potential energy supply portfolios through brainstorming. This is performed with the help of a panel of experts. The portfolios are then screened using a portfolio optimization strategy based on the GP technique, which considers all technical and quantitative factors. As a result, a portfolio based on technical and quantitative elements is created.

The panel of experts is asked to identify qualitative criteria for evaluating identified and screened portfolios in the next iteration and technical and quantitative criteria. The expert panel was asked to set goals and attributes for evaluating options in this case. Using the MAVT approach, attribute weights, and partial value functions are elicited and run in the model. The selected portfolio is next subjected to sensitivity analysis based on the results of the MAVT approach. Sensitivity analysis involves shocking the model by changing variables and comparing the results to the baseline.

The portfolio built using the model's primary inputs is referred to as the base case. The portfolio is recommended for adoption and implementation if the requirements are met. If the result is unsatisfactory, the model findings are sent back to the analyst for further refining, and the process is repeated iteratively (See Figure 12) until a solution is found. The MAVT framework incorporates the goals employed in the augmented Chebychev GP technique, establishing a link between the two techniques. The MAVT technique included softer requirements that the augmented Chebychev GP technique could not handle. Following the processes outlined in Figure 12, the results of the GP technique are further reviewed using an additive MAVT technique to address the problem.

Figure 19: The decision model



Source: Adapted from Mintzberg et al., 1976

5.6 Justification for the use of goal programming and the value/utility function approach for the present study

When there are several options, the GP technique is important since it allows one to narrow down the search for the best option, as mentioned in Section 3.3.2. Complexity, robustness, transparency and cost considerations were considered. The type and nature of the available data largely determine the MCDA approach to be adopted for a particular multi-criteria decision problem. Some MCDA techniques only take quantitative data, while some work with both types of data.

The MAVT technique is considered a robust and coherent framework that is both stronger theoretically and more transparent to users/decision-makers, Section 3.3.5. The MAVT is also easy to use, is more transparent to users, is theoretically well established and axiomatized, and uses both quantitative in the first stages and qualitative data in the later stages. The study aimed to aid thinking and decision-making when formulating and structuring energy access policies aimed at benefiting the poor.

The study also aimed to provide stakeholders with the opportunity to explore their priorities and values and consider the views and values of other stakeholders to the problem. The MAVT technique is suitable for achieving this objective as it improves the understanding of the problem. It forces stakeholders to compose a value function that represents preferences. The MAVT technique is credited for reducing the amount of information needed to comprehend the problem and decision outcomes fully.

Also, the MAVT approach provides a communication platform for reasoning and negotiations. MAVT also allows the incorporation of the diverse views of stakeholder groups in constructing criteria tree, alternatives and the configuration of the value function. Lastly, an additional justification for using MAVT is the ease of use of software to test the robustness of the results using sensitivity analysis (See Appendix D).

5.7 Discussion

Research revealed that no definite evaluation criteria framework exists for the ex-ante assessment of low-income household energy supply interventions, actions, plans, or policies for any given objective or set of goals. Therefore, this justified the development of a novel and a more refined framework. The literature review revealed five key evaluation criteria groups used internationally to evaluate energy supply development plans for low-income households. These criteria groups are technical, economic, environmental, socio-economic and political.

The conceptual and preliminary evaluation criteria framework developed includes eight principal evaluation criteria. Further analysis and literature review showed that a conceptual, preliminary evaluation framework has limited suitability in evaluating energy supply development plans. The framework developed builds on the conceptual framework and was created by reviewing the literature on low-income household energy supply policy development. The criteria evaluation framework combines and considers all the pertinent features of development plans aimed at increasing access to energy by poor communities living in rural and informal urban areas. .

5.8 Chapter conclusion

The established evaluation criteria framework can be used by energy planning authorities and decision-makers to improve the creation and development of energy access plans for low-income households and detect policy flaws. This framework creates a unique and universal agenda for evaluating the quality of energy access development strategies.

This framework can be used by energy planning authorities and decision-makers to overcome considerable hurdles in the design and execution of energy access plans. The first step of the two-stage MCDA framework proposed is demonstrated in the next chapter.

CHAPTER 6

SELECTION OF A PORTFOLIO OF ENERGY SUPPLY OPTIONS FOR LOW-INCOME HOUSEHOLDS IN SOUTH AFRICA USING THE GOAL PROGRAMMING TECHNIQUE

6.0 Chapter introduction

This chapter aims to demonstrate the first phase of the two-stage MCDA framework discussed in Chapter 5. A decision needs to be taken for an energy access problem discussed in Chapter 1 (see Section 1.2). To this end, the previously developed framework was adapted and applied to a typical energy access problem aimed at benefiting the poor. The idea was to visualise the possible real-life solutions for the authorities responsible for deciding what options to include in the portfolio. By using the developed framework, more time can be spent on the modelling and the optimisation process. The chapter examines the trade-offs and synergies inherent in making energy choices and points to overlooked opportunities in addressing the energy poverty problem in the South African context.

6.1 Outline of the model

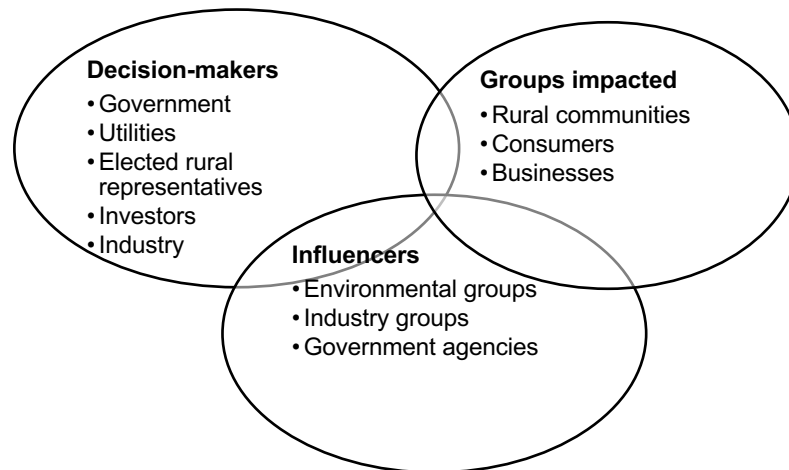
As discussed in the previous chapter, the procedure applied was divided into four sections: decision recognition, decision diagnosis, development, selection, and evaluation of strategies. Multiple objective linear programming (MOLP) was introduced in the first stage. In the second stage, covering the development of solutions based on the outcomes of GP, portfolio optimisation was applied to maximise the value of the portfolio subject to a set of constraints.

6.1.1 Stakeholders

The acceptable compromise solution in MCDA is determined by the interests and values of the problem's stakeholders. As a result, a stakeholder analysis was carried out to identify the problem's primary stakeholders and interest groups. During the stakeholder identification and mapping process, the snowball sampling technique was used. Snowball sampling is a non-probability sampling procedure in which existing subjects provide referrals to recruit samples required for a research study (Groenewald, 2004; Cohen and Arieli, 2011). The stakeholders were drawn from a list of participants who attended a conference on Poverty and Inequality, which was organised by the Mandela Initiative and the University of Johannesburg in 2016. The conference took place in June 2016 at Mulder's Drift in Gauteng over three days and was attended by participants from government, non-governmental organisations and businesses. Therefore, the key stakeholders to the problem were identified as individuals and

organisations involved in the energy sector. These are individuals and organisations who also have vested interests in its outcome. Figure 20 summarises the different stakeholders impacting and impacted by the energy supply technology decision for low-income households. These were identified through the stakeholder analysis conducted.

Figure 20: Stakeholders to the problem



Source: Strategic dialogues

The number of potential stakeholders was considered too large for it to be feasible to consider all their viewpoints in a model. As a result, only a limited number of experts from selected organisations were considered to have an interest in the problem. The initial database of stakeholders contained over 200 individuals from more than 40 organisations.

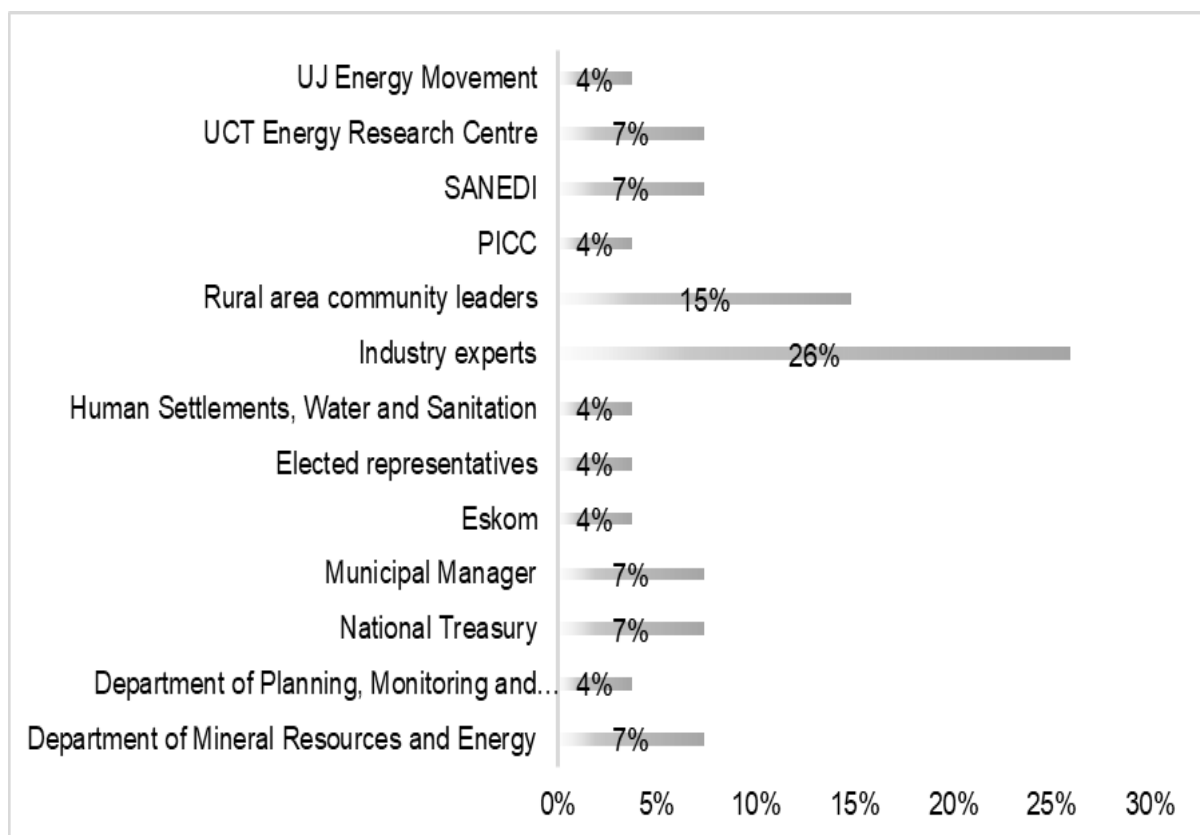
Given this vast pool of stakeholders to the problems, budgetary and time constraints, it was not feasible to solicit the views of all stakeholders to the problem. Therefore, it was deemed necessary to select a smaller number of key organisations whose opinions could be considered representative of the broader stakeholders to the problem.

In the end, 27 experts from the energy industry, academia, government, elected representatives, community leaders, the private sector, and non-governmental organisations were involved in developing and applying the model. Again, these were selected as part of the stakeholder analysis conducted. The snowball sampling technique was applied to recruit subjects from their acquaintances. Purposive sampling was also applied alongside snowball sampling to select affected rural communities and their representatives. Purposive sampling is also a non-probability approach in which subjects are selected based on the characteristics of a population and the objective of the study using some specifically defined criteria. (Ritchie et al., 2013). The justification for using the snowball and purposive sampling techniques was

that experts on the subject were unknown, and rare and it was difficult to choose subjects to assemble them as samples for research.

The first group was drawn from a panel of experts of attended a conference on Poverty and Inequality discussed earlier. Figure 21 shows the proportions of individuals that were engaged. All strategic dialogues were conducted with the commitment to confidentiality and the University of Cape Town’s Ethics Code. Therefore, the study did not single out any individual. The list of institutions was validated and considered sufficient and representative by the panel. The panel concurred that these are vital institutions actively involved in the low-income household research and policy formulation and implementation in South Africa.

Figure 21: Participants of the strategic dialogues by the institution



6.1.2 Selecting options for action, attributes and indicators

The panel of experts was requested to characterize the problem and provide possible solutions for distributing energy to low-income people living in isolated rural areas and informal urban settlements during the discussions, which were conducted using the PESTEL technique.. Engagements took the form of iterative two-phased face to face and virtual panel

interviews. During the first round of interviews. Two sets of themed questions were asked, namely,

- Question 1: What are the key national priorities insofar as energy supply is concerned for deprived communities residing in isolated and unelectrified rural areas and informal settlements?
- Question 2: What are the key barriers preventing the implementation of past and planned interventions?

Feedback from the above sessions was collected, collated, and reviewed iteratively with the panel of experts to identify and define feasible and infeasible energy supply technologies and the corresponding technical parameters for comparing these technologies with barriers. The second round of interviews was conducted to review and validate the resulting list of the various energy technology options and the technical parameters. Ten energy supply technologies were identified for multiple uses; cooking, lighting, entertainment and cell phone charging, refrigeration, laundry, home maintenance, and water heating .

The ten energy supply technologies are fuelwood, kerosene, denatured bioethanol fuel, LPG, existing grid electricity (rural electrification), micro-grids based on CCGT, diesel generator scheme based on the open cycle gas turbine (OCGT) technology, concentrating solar power (CSP), crystalline silicon (c-Si) solar PV and wind. The panel of experts also agreed on a list of the cost and technical parameters for assessing the energy supply technologies.

The final list of candidate technologies was circulated among the panel for feedback and endorsement in reaching the agreement. The agreed list was then incorporated into the study. Table 7 provides the list of the ten energy supply technologies suitable for deployment in low-income households in South Africa for different applications. Table 8 provides detailed summaries of these technologies.

Table 7: Selected energy conversion technologies

Source [energy technology]	Uses					
	Cooking	Lighting	Entertainment and cell phone charging	Refrigeration	Laundry and home maintenance	Geyser
1. Fuelwood	√	×	×	×	×	×

Source [energy technology]	Uses					
	Cooking	Lighting	Entertainment and cell phone charging	Refrigeration	Laundry and home maintenance	Geyser
2. Kerosene	√	√	×	×	×	×
3. Bioethanol fuel	√	√	×	×	×	×
4. LPG	√	√	×	×	×	×
5. Grid electrification	√	√	√	√	√	√
6. CCGT	√	√	√	√	√	√
7. Diesel generator	√	√	√	√	√	√
8. Solar with storage	√	√	√	√	√	√
9. Solar PV	√	√	√	√	√	√
10. Wind	√	√	√	√	√	√

Source: Study strategic dialogues, 2020

Table 8: Technology descriptions

Source/ Technology	Strength	Main drawback	Key discussion points and takeaways
1. Firewood	Fuelwood is cheap and mostly free in rural areas and is a critical emergency backup fuel. (Guild and Shackleton, 2018).	Burning firewood is known to cause fire hazards and respiratory health problems. Uncontrolled use has led to deforestation and natural habitat loss.	Fuelwood is a vital and secure fuel for many poor households. Use of efficient technologies such as cookstoves used to reduce emissions and quantities used. Fuelwood trade is a recognised source of informal employment (earnings exceed the international poverty line and social grants). (Guild and Shackleton, 2018).
2. Kerosene	Kerosene and devices used are affordable and readily available to	Associated with several problems such as the death of children who	Currently, there are no known technologies and innovations that have been developed to

Source/ Technology	Strength	Main drawback	Key discussion points and takeaways
	many low-income households and is a vital emergency backup fuel.	drink it accidentally, the spread of fire, burn injuries and indoor air pollution.	deal with the adverse effects of kerosene.
3. Bioethanol	Bioethanol is produced locally and is considered a safer alternative to kerosene and firewood.	High capital costs. Bioethanol fuel is not readily available in remote rural villages.	Performance optimisation opportunities exist and can be used in many applications. Given the high fuel efficiency, bioethanol gel is one of the most popular sources of energy for cooking in poor communities.
4. LPG	LPG is considered a safer alternative to kerosene.	High lifecycle costs with fuel costs indexed to the exchange rate. LPG has a high calorific value and is not readily available in remote rural villages.	Performance optimisation opportunities exist and can be used in many applications. Given the high fuel efficiency, LPG is one of the most popular sources of energy for cooking in poor communities.
5. Grid electrification	Source of reliable power and is both socially and politically acceptable – electricity is considered a status symbol in many rural communities.	Electrifying low-income households living in sparsely populated areas require significant upfront capital expenditure and operational subsidies.	Electrification programmes can be successful and sustainable if combined with other sources of energy such as renewables.
6. CCGT	Gas is considered a clean-burning fuel and one of the most cost-efficient sources of energy for cooking and is cheaper than grid-connected electricity.	Gas prices are susceptible to exchange rate movements. Prices are determined by global petroleum price trends and the exchange rate.	Combinations with other renewable energy sources such as rooftop solar for the provision of cooking and lighting purposes are very useful.
7. Diesel generator (OCGT)	Diesel generators are proven and readily available technologies.	Diesel is costly and not easily accessible, maintenance can also be a challenge and these systems are very noisy, highly polluting. Intended to be used during peak periods and emergencies.	Diesel continues to be a useful emergency backup source of energy.

Source/ Technology	Strength	Main drawback	Key discussion points and takeaways
8. Solar PV	Clean, no fuel costs, low operational costs, modular, transferable and low emission.	High capital costs and highly intermittent production.	The global solar industry continues to invest in innovative solutions and affordable energy storage technologies.
9. Wind	Clean, no fuel costs and these systems are modular and easily transferable.	Wind turbine requires a higher level of maintenance – brake pads and greasing of moving components and refurbishment of rotor blades.	Potential to meet water pumping needs among remote rural villages and the replacement of expensive diesel-based water pumps.
10. Solar with storage	Clean, no fuel costs, low operational costs, modular, transferable and low emission. Suitable for constant output in a micro-grid setup.	High capital costs in particular the energy storage component.	The global solar industry continues to invest in innovative solutions such as light-emitting diode lamps and displays; and affordable energy storage technologies.

Source: Muller et al. (2003), Sovacool (2011), Daw (2013), Silwal and McKay (2015), Gross et al, (2017) Gould and Urpelainen (2018), (Guild and Shackleton, 2018), Dalberg (2018), Barasa (2018)

6.1.3 Options for action

In discussions held with the panel of experts, it emerged that energy consumption patterns in isolated rural areas remain low because of the lack of adequate, affordable, reliable, quality, safe and environmentally sound energy services to support development. The South African government electrification programme has not alleviated multiple fuel use, and neither has it helped in reducing poverty. Even for households that receive and depend on the FBE grant, research shows that households use the full allocation and then revert to the previously used energy sources (candle, paraffin, wood) or are forced to use “less official solutions”. This mismatch between consumer demand and supply strategies needs to be addressed to benefit the government, the taxpayer and the beneficiaries, i.e., low-income households. According to the panel of experts, in non-electrified low-income communities, kerosene and firewood have remained key sources of choice and still play a significant role in cooking and lighting.

Low economic activity in rural and informal low-income areas has meant low energy demand. This evidence suggests that complementary non-electric fuels, appliances, safe and efficient

solutions should be considered when crafting energy supply interventions centred on extending the central grid. The focus needs to shift from electrification at all costs, to include all available and feasible energy sources. Increasing access to energy should not be considered a goal. Instead, energy access goals should incorporate other goals, such as minimising negative health and environmental impacts and social opportunity costs. The GP technique was deemed useful in situations where multiple objectives have to be considered in the decision-making process.

6.2 Selecting portfolios of action: multi-objective linear programming procedure

6.2.1 Defining the decision variables

As previously noted in Section 6.1, the decision to be made is related to two sets of decisions, the determination of the installed capacities of energy supply options (labelled Y) to be included in an energy mix in gigajoules (GJ) for different energy uses and the allocation of this capacity (labelled X) to satisfy demand under different future circumstances. In other words, there were two levels of decision variables, namely:

- i. What technologies are installed and how much?
- ii. How was this allocated between thermal and electrical energy demands under different scenarios?

This differentiation was essential under multiple scenarios as the same installed capacity may be used differently under different scenarios with different levels of availability under different scenarios. While it may sound a bit artificial to talk of 'installed capacity' of say fuelwood, it was probably easier to formally work in such terms, where this then represents a maximum resource to be made available independent of the scenario.

The units for the decision variables were in GJ for all applications. In cases where the energy units were measured in kWh, such as rooftop solar and grid electricity, these were converted to GJ using a conversion factor of $1 \text{ kWh} = 0.0036 \text{ GJ}$ (See Appendix B). The GJ is a useful unit of energy for comparing the amount and cost of heat energy provided by different types of energy. In other words, the volume of any type of energy can be converted to GJ so that they can be compared.

Data limitations restricted the depth of the analysis on the energy consumption among the poor in South Africa. Nonetheless, case studies could be used to infer energy consumption among low-income households in South Africa. One was a study conducted by Menéndez and Curt (2013), who posited that in regions that do not require space heating, domestic energy consumption per capita for a remote and small rural village in the Iringa Region of Tanzania

was estimated at 4.487GJ per year. Similarly, Simmonds and Mammon (1996); the Ekurhuleni Metropolitan Municipality (EMM) (2006); Winkler (2006); City of Cape Town Metropolitan Municipality (CTMM) (2006); City of Johannesburg Metropolitan Municipality (COJMM) (2007); Dalberg (2018) and Barasa (2018) estimated that low-income households require approximately 18.33GJ per year to meet basic energy needs. In this study, a representative community was defined as a community comprised of 500 households with a nominal energy demand of 1 075GJ per year for all uses. Each household was comprised of a family of five with a nominal energy demand of 21.5 GJ per household per annum. The demand estimate was based on figures obtained from the case studies discussed above.

Ten different energy supply options (labelled Y) were considered for a representative community, namely firewood, kerosene, bioethanol fuel, LPG, grid electricity, CCGT, OCGT, solar PV, solar thermal, and wind were to be deployed to form an energy mix in GJ (labelled $j = 1, \dots, 10$). The decision variables for the model were thus defined as:

Y_j : provided (installed) capacity in GJ for technology j ($j = 1, \dots, 10$)

X_{ijk} : quantity of installed technology j allocated to serving energy needs of six different uses i ($i = 1, \dots, 6$) under conditions of three different scenarios k ($k = 1, \dots, 3$).

The six different energy uses (i), namely cooking; lighting; entertainment and cell phone charging; refrigeration; laundry and home maintenance; and water heating. As mentioned in Section 6.2.2, if fuelwood, kerosene and bioethanol gel were deployed, they would only be used for cooking. Grid electricity, CCGT and diesel generator would be used for all applications. Solar would be used exclusively for all applications except for cooking. Wind would also be used for all applications except for cooking and water heating.

The developed model considered three climate change scenarios, which emerged from the strategic dialogues conducted. The first scenario considered was the **status quo scenario** (k_1); this is the status quo scenario modelled based on available information. The second scenario was termed the **warmer and dry climate scenario** (k_2); this is a climate change scenario in which the South African climate becomes warmer, characterised by hot and drier weather conditions. The scenario was based on the year 2040 ($t_{=2040}$); The third scenario was termed the **cold and wetter climate scenario** (k_2); this is a climate change scenario in which the South African climate becomes colder, characterised by cold and wet weather conditions. The scenario was also based on the year 2040 ($t_{=2040}$). These scenarios are discussed in detail later in this chapter.

6.2.2 Constraints

The model developed for this study incorporated hard constraints based on the estimated household energy requirements for satisfying the basic needs discussed above. Two classes of hard constraints were thus defined as:

1. **Capacity constraint:** $\sum_i X_{ijk} \leq Y_j$ for all j and for each scenario k .
2. **Demand constraint:** $\sum_j X_{ijk} \geq \text{demand}$ for use i under scenario k for all i and k .
 X_{ijk} denotes GJ of usable power for use i under scenario k delivered by an allocation of 1 GJ of installed capacity of technology j to this usage. In some cases, this parameter had a value 0 (not appropriate), in many cases it may be 1, but represent efficiency in other cases (e.g., wind and solar power under certain conditions).

6.2.3 Objectives

The study objectives were elicited as part of the second round of the strategic dialogues which were conducted with the panel of experts and community representatives. The panel of experts and community representatives were asked the question, “*from a maximisation and minimisation standpoint, what would you consider to be an important objective when making a decision to select energy supply technologies for low-income households?*”. Feedback from the strategic dialogues was collected, collated and reviewed iteratively with the panel of experts to identify and define the objectives. Again, in reaching the agreement, the final list of objectives was circulated among the panel for feedback and endorsement. The agreed list was then incorporated into the model. From the engagements, the decision-makers, represented by a panel of experts identified and agreed on four objectives, namely, *minimisation of upfront capital costs, minimisation of operational lifecycle costs, minimisation of drudgery*²⁰; and *minimisation of emissions*²¹.

The first objective (labelled z_1), related to the minimisation of capital costs (labelled K) in Rand per gigajoule (R/GJ) formulated as follows:

$$z_1 = \sum_{j=1}^n Y_j K_j \quad \text{Equation 10}$$

The initial capital costs are not scenario dependent. The capital cost estimates for z_1 were based on cost and performance data obtained from case study reports and publications (Eskom, 2020; Gross et al., 2017; Clean Cooking Alliance (cleancookstoves.org); Frink et al., 2017; Dalberg, 2018), Barasa (2018).

²⁰ Amount of time that households spend collecting fuels and maintaining systems.

²¹ HAP refers to pollution generated from burning fuels by households resulting in air pollution inside the house.

The second objective (labelled z_{2k}) related to the minimisation of the operational lifecycle costs for meeting useful energy demand (labelled R) in R/GJ under the three different scenarios and thus formulated as three distinct goals as follows:

$$z_{2k} = \sum_i \sum_j X_{ijk} R_{ijk} \quad \text{Equation 11}$$

Running costs for R_{ijk} comprised of the fuel and ongoing operation and maintenance (O&M) and appliance costs. In other words:

$$R_{ijk} = \sum_{t=1}^n \frac{\text{Fuel cost } (t) + \text{Operational costs} + \text{appliance cost } (t)}{(1+r)^t} \quad \text{Equation 12}$$

Where: *fuel cost* (t) is the total fuel used multiplied by the cost of each fuel in each year; *Operational costs* is the present value of the ongoing operational costs, *appliance cost* (t) is household expenditure on energy appliances each year and r is the discount rate, set at 8 per cent real (as used in the IRP for South Africa).

A consumer price index (CPI) of 4.5 per cent was used for normalisation to 2020 Rand values. These figures were obtained from various case studies and experiments (Clean Cooking Alliance, 2021; Joburg Firewood Company, 2021, Fuel Retailer Association of Southern Africa, 2021; DMRE, 2021; Eskom, 2021; Dalberg, 2018, Barasa, (2018). These studies estimated the comparative costs of fuel of different technologies.

Appliance consumption data were obtained from the online Eskom energy appliance calculator and appliance ownership estimates provided by the Clean Cooking Alliance (Clean Cooking Alliance, 2021) and online retail stores (Sustainable Online Site (www.sustainable.co.za); Take a Lot Online Site (www.takealot.co.za) Makro Online Site (www.makro.co.za); Builders Warehouse Online Site (www.builders.co.za)).

Appliances used in the case studies and experiments were those that are 'commonly used' in low-income settlements. The case studies and trials undertook experiments conducted in low-income settlements using energy sources and appliances that local residents to cook a range of typical meals, including staple starch meals (mealie meal, rice and pasta), quick-to-medium stews (liver, chicken and vegetables) and longer-cooking meals (beef stews, beef tripe, samp and beans).

The third objective (labelled z_{3k}) related to the minimisation of drudgery (labelled D) in hours per GJ (H/GJ) under the three different scenarios formulated as follows:

$$z_{3k} = \sum_i \sum_j X_{ijk} D_{ijk} \quad \text{Equation 13}$$

The estimate for time spent collecting firewood and managing the systems for z_{3k} were obtained using the time taken to complete the activities obtained from (Calvo, 1994; Matsika et al, 2013; Stats SA, 2019). According to Matsika et al, 2013, households in remote rural villages take four trips per week to collect firewood per household with each trip lasting two hours.

The fourth objective (labelled z_{4k}) related to the minimisation of pollutants²² (labelled E) namely carbon dioxide (CO_2), carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$). This implied the following formulation for pollutants:

$$z_{4k} = \sum_i \sum_j X_{ijk} E_{ijk} \quad \text{Equation 14}$$

Emissions and HAP values for z_{4k} were obtained from WHO Guidelines for indoor air quality (<https://undark.org/breathtaking/>) as well as the Clean Cooking Alliance database (Clean Cooking Alliance, 2021). Exposure testing for all fuels was not conducted as part of the research.

6.2.4 Scenarios

The model developed considered three climate change scenarios. Scenarios were incorporated into the GP mode to evaluate a range of possible future trends and uncertainties that may alter the decisions made based on the framework developed. The scenario outcomes were informed by different policy directions, emerging technological trends and uncertainties. Climate change is already affecting the world's energy mix. For example, recent data emerging from studies conducted by the International Monetary Fund has shown that a one-degree Celsius increase in temperature will raise Sub-Saharan electricity consumption by about seven per cent (Yao, 2021).

Climate change reduces energy availability, decreases quality, impacts sustainable development and impeded people's access to energy. Climate resilience is an emerging concept that is increasingly used to represent the durability and stable performance of energy systems against extreme climate events. Performance under conditions of each scenario as an objective represented was explicitly in its own right as postulated in Stewart et al. (2013),

²² The Clean Cooking Alliance links increased exposure to CO_2 , CO and $PM_{2.5}$, to increases in premature death as well as a range of serious respiratory and cardiovascular effects (Clean Cooking Alliance, 2011).

labelled z_{rk} (fundamental objective r , scenario k). In the energy access problem, we, therefore, ended up with ten objectives structured as follows:

$$z_1, z_{21}, z_{22}, z_{23}, z_{31}, z_{32}, z_{33}, z_{41}, z_{42}, z_{43} \quad \text{Equation 15}$$

The objectives were handled just like any other. The double indexed notation for some objectives was observed to be less convenient for ease of defining the GP structure. We thus introduced a parallel alternative notation. For ease of display and convenience in defining and describing the GP, the study adopted a notation of parenthetical indices, say $z_{(r)}$ to represent the r^{th} element in the vector defined in (Equation 15). For example, $z_{(4)} = z_{23}$.

The scenarios adopted for the study were elicited as part of the second round of the strategic dialogues which were conducted with the panel of experts and community representatives. The panel of experts and community representatives were asked the question “*what are the possible substantial uncertainties that could emerge after the basic policy decisions are implemented, within the operational lifetimes of the relevant technology installations?*”. Feedback was collected, collated and reviewed iteratively with the panel of experts to identify and define the scenarios. The final list of scenarios was circulated among the panel for feedback and endorsement in reaching the agreement. The agreed list of candidate scenarios was then incorporated into the study. The technical characteristics and parameters for each scenario are summarised in Table 9. The three scenarios that emerged from the strategic dialogues are summarised below.

- i. **Status quo scenario** (k_1), this is the status quo scenario modelled based on available information. It assumed a community residing in an isolated rural village where firewood is freely available. It must be noted here that the efficacy of the modelled status quo was hinged on consideration of climate change, including extreme events, to ensure the reliable performance of energy systems in the long run. This helped in dealing with uncertainties that emerged after the selected investments were made;
- ii. **Warmer and dry climate scenario** (k_2): this is a climate change scenario in which the South African climate becomes warmer, characterised by hot and drier weather conditions. This modelled scenario is synonymous with a sustained El Niño event. An El Niño is an ocean-atmosphere occurrence that affects global weather patterns. It is part of a broader climate pattern known as the El Niño Southern Oscillation (IPCC²³, 2016). El Niño results in drier-than-normal conditions in

²³ Intergovernmental Panel on Climate Change.

Southern Africa (NASA²⁴, 2021). The IPCC (2016) predicts 20 per cent more drought months over most of the southern hemisphere by 2030. Since El Niño weather tends to be warmer and drier overall, people will require less energy for heating and more for cooling, which affects their overall energy usage (IPCC, 2016). Temperature increases will result in a net increase in energy demand in summer. Climate change was assumed to affect the ability to produce and deliver energy reliably negatively. Under this scenario, climate change was also assumed to reduce the amount of water available to produce and transport energy or extract fuel from the grid, fuelwood, bioethanol, fuel and kerosene. The scenario was based on the year 2040 ($t_{=2040}$); and

- iii. **Cold and wetter climate scenario (k_2)**: this is a climate change scenario in which the South African climate becomes colder, characterised by cold and wet weather conditions. This scenario is synonymous with a sustained La Niña event. La Niña is the opposite phase of El Niño (IPCC, 2016). La Niña results in wetter-than-normal conditions in Southern Africa (NASA, 2021). La Niña events may cause people to use more oil, natural gas and electricity to power their heating systems and use less energy on cooling (IPCC, 2016). Temperature decreases will increase energy demand in winter. Temperature extremes, especially extreme cold, were also assumed to encumber the efficient extraction, production and delivery of energy from certain technologies. For example, cloud cover, and extremely cold conditions will reduce the conversion efficiency and electricity output in all solar and wind technologies (Nik et al., 2021). Simultaneous extreme cold, high winds, heavy rain, snow and ice storms are assumed to reduce the amount of available resources needed to produce energy or extract fuel from sources such as solar and bioethanol fuel (Nik et al., 2021). The scenario was based on the year 2040 ($t_{=2040}$).

Table 9 summarises the cost and technical features of each technology and objective under each of the three scenarios discussed above.

²⁴ National Aeronautics and Space Administration.

Table 9: Summary of technology characteristics

1. Status quo										
Technology characteristics										
	Firewood	Kerosene	Bioethanol fuel	LPG	Grid electricity	CCGT	OCGT	Solar PV	Solar with stor:	Wind
Lifecycle capital costs (R/GJ) [K]	37	47	57	513	1 246	988	4 414	3 276	6 691	2 700
Lifecycle fuel and O&M costs (R/GJ)										
Lifecycle fuel costs (R/GJ) [R]	-	1 331	1 074	923	3 578	1 378	2 147	-	-	-
Lifecycle O&M costs (R/GJ)	75	66	95	107	95	292	708	884	1 096	1 150
	75.35	1 397.25	1 169.37	1 030.36	3 672.76	1 670.20	2 854.96	883.52	1 096.14	1 150.36
Drudgery (Hrs/GJ)	8.43	3.02	1.40	3.02	0.11	0.11	0.11	0.16	0.16	0.27
Pollutants										
Carbon dioxide (kJ/GJ)	112.00	71.50	35.40	31.55	94.00	63.10	74.10	7.20	7.20	7.20
Carbon monoxide (kg/GJ)	5.60	5.60	4.80	0.15	-	0.15	5.60	-	-	-
Particulate Matter (PM2.5) (kg/GJ)	736.00	15.70	7.69	6.97	-	13.94	368.00	-	-	-
	853.60	92.80	47.89	38.67	94.00	77.19	447.70	7.20	7.20	7.20
2. Warmer and dry conditions										
Technology characteristics										
	Firewood	Kerosene	Bioethanol fuel	LPG	Grid electricity	CCGT	OCGT	Solar PV	Solar with stor:	Wind
Lifecycle fuel and O&M costs (R/GJ)										
Lifecycle fuel costs (R/GJ) [R]	65.00	2 661.94	1 289.14	922.97	1 788.78	2 756.88	2 147.04	-	-	-
Lifecycle O&M costs (R/GJ)	150.71	132.55	190.18	107.40	190.39	291.76	707.92	883.52	1 096.14	1 150.36
	215.71	2 794.49	1 479.32	1 030.36	1 979.17	3 048.64	2 854.96	883.52	1 096.14	1 150.36
Drudgery (Hrs/GJ)	16.85	3.02	1.40	3.02	0.11	0.11	0.11	0.16	0.16	0.27
Pollutants										
Carbon dioxide (kJ/GJ)	112.00	71.50	35.40	31.55	94.00	63.10	74.10	7.20	7.20	7.20
Carbon monoxide (kg/GJ)	5.60	5.60	4.80	0.15	-	0.15	5.60	-	-	-
Particulate Matter (PM2.5) (kg/GJ)	736.00	15.70	7.69	6.97	-	13.94	368.00	-	-	-
	853.60	92.80	47.89	38.67	94.00	77.19	447.70	7.20	7.20	7.20
3. Cold and wet conditions										
Technology characteristics										
	Firewood	Kerosene	Bioethanol fuel	LPG	Grid electricity	CCGT	OCGT	Solar PV	Solar with stor:	Wind
Lifecycle fuel and O&M costs (R/GJ)										
Lifecycle fuel costs (R/GJ) [R]	-	2 661.94	537.14	922.97	4 293.07	2 756.88	4 294.08	-	-	-
Lifecycle O&M costs (R/GJ)	75.35	132.55	47.54	107.40	95.20	583.51	1 415.83	883.52	1 096.14	2 300.71
	75.35	2 794.49	584.69	1 030.36	4 388.27	3 340.39	5 709.91	883.52	1 096.14	2 300.71
Drudgery (Hrs/GJ)	8.43	3.02	0.70	3.02	0.11	0.22	0.22	0.16	0.16	0.27
Pollutants										
Carbon dioxide (kJ/GJ)	112.00	71.50	35.40	31.55	94.00	63.10	74.10	7.20	7.20	7.20
Carbon monoxide (kg/GJ)	5.60	5.60	4.80	0.15	-	0.15	5.60	-	-	-
Particulate Matter (PM2.5) (kg/GJ)	736.00	15.70	7.69	6.97	-	13.94	368.00	-	-	-
	853.60	92.80	47.89	38.67	94.00	77.19	447.70	7.20	7.20	7.20

Source: Calvo, 1994; Matsika et al., 2013; Gross, 2015; Frink et al., 2017; Dalberg, 2018; Barasa, 2018; Global Alliance for Clean Cookstoves, 2021; Online Stores; Fuel Retailer Association of Southern Africa, 2021; DMRE, 2021; Eskom, 2021.

6.2.5 Payoff table

In MOLP modelling, one must ensure that the solutions derived via individual objective function optimization are truly efficient. This was accomplished in this work by optimizing each goal function and constructing a payoff table with only efficient solutions. The payoff table is used in the same way as the reference point technique (Wierzbicki, 1999) to ensure Pareto optimality. A payoff table is a matrix containing the results of individual objective function optimization.. A payoff table was therefore constructed for all uses. In principle, the payoff table was obtained by minimizing $z_k + \epsilon \sum_{r \neq k} z_r$ for each of the following objectives in turn:

$$z_1 = \sum_{j=1}^n Y_j K_j \quad \text{Equation 16}$$

$$z_{2k} = \sum_i \sum_j X_{ijk} R_{ijk} \quad \text{Equation 17}$$

$$z_{3k} = \sum_i \sum_j X_{ijk} D_{ijk} \quad \text{Equation 18}$$

$$z_{4k} = \sum_i \sum_j X_{ijk} E_{ijk} \quad \text{Equation 19}$$

Subject to the following constraints:

Capacity constraint: $\sum_i X_{ijk} \leq Y_j$ for all j and for each scenario k .

Demand constraint: $\sum_j X_{ijk} \geq \text{demand for use } i \text{ under scenario } k$ for all i and k .

Table 10 presents a summary of the results, levels of performance obtained for all objectives.

Table 10: Performance levels obtained

Objectives being minimised	Values obtained for:									
	$Z_{(1)}$	$Z_{(2)}$	$Z_{(3)}$	$Z_{(4)}$	$Z_{(5)}$	$Z_{(6)}$	$Z_{(7)}$	$Z_{(8)}$	$Z_{(9)}$	$Z_{(10)}$
$Z_{(1)}$	6620.06	11321.66	20713.94	21847.15	44.26	86.60	44.94	4792.38	4792.38	4792.38
$Z_{(2)}$	28383.75	5784.08	11726.32	28450.80	43.34	87.01	44.66	4334.29	4789.69	4898.29
$Z_{(3)}$	26822.91	21563.92	6082.02	28450.80	44.43	85.61	43.27	4838.43	4330.97	4898.29
$Z_{(4)}$	29478.39	21563.92	11726.32	6304.57	44.43	87.01	44.66	4838.43	4789.69	4338.53
$Z_{(5)}$	14376.61	40929.32	11726.32	28450.80	1.20	87.01	44.66	1047.54	4789.69	4898.29

$Z_{(6)}$	18844.25	21563.92	32568.03	28450.80	44.43	1.15	2.31	4838.43	824.65	4898.29
$Z_{(7)}$	13751.83	21563.92	21143.14	28450.80	44.43	1.15	1.15	4838.43	1004.19	4898.29
$Z_{(8)}$	30663.96	10584.01	11726.32	28450.80	16.19	87.01	44.66	238.43	4789.69	4898.29
$Z_{(9)}$	29153.02	21563.92	10176.51	28450.80	44.43	16.12	16.12	4838.43	235.11	4898.29
$Z_{(10)}$	31758.60	21563.92	11726.32	11104.50	44.43	87.01	44.66	4838.43	4789.69	242.67
Range of values (R_k)	25138.54	35145.24	26486.02	22146.23	43.22	85.86	43.78	4600.00	4557.27	4655.62

Source: MOLP Model

6.2.6 Weights

For the overall performance level to be calculated, a set of weights was placed on each objective to represent the relative importance of the goal to the computed score. A goal's relative importance refers to how important it is in comparison to other goals (Belton and Gear, 1997, see also Section 3.3.2). The measures of performance were all weighted by inverse range. The chosen weights were defined by the importance weight divided by the range in the payoff table. The objectives were left unscaled, and the weights were defined as $(1/R_{(r)}) \times (\text{importance weight})$. The weights were thus calculated by dividing each *importance weight* by the range of values $R_{(r)}$ in the payoff table above.

The weighting scales all performance measures to have a range of one unit from best to worst in the payoff table, placing equal importance on achieving a swing from worst to the best outcome for each objective. The decision-makers were requested to assess the relative importance of the worst-to-best swings for each objective. The decision-makers are asked to assess their worst outcome in each criterion and choose which criterion they would prefer to modify from its worst to its best outcome using the Swing technique (Goodwin and Wright, 2001). This criterion will receive the largest number of points, such as 100, and will be removed from the procedure. After then, the process is repeated with the remaining conditions. The next most important criterion will be given a number that is proportional to the most important (therefore their points show their relative importance), and so on. The agreed relative importance obtained for the four objectives was equal across all the four objectives.

6.3 Selecting portfolios of action: goal programming

The present study used the augmented Chebychev GP technique. The GP technique was considered well suited for this kind of problem because decision-makers were more interested in obtaining a balance between the competing objectives. The augmented Chebychev GP metric utilises the Chebychev distance metric, which emphasizes justice and balance rather than ruthless optimisation. Introduced by Flavell in 1976, the Chebychev GP metric seeks to minimise the maximum unwanted weighted deviation rather than the sum of deviations:

$$D = \max_k \{ w_k^- d_k^- + w_k^+ d_k^+ \}. \quad \text{Equation 20}$$

For this reason, the Chebychev GP metric is sometimes termed the *Minmax* GP. To avoid problems when one goal is hard to achieve, the Chebychev GP adopted for the study was to minimise the sum of deviation: $D + \epsilon \sum_{k=1}^K \{ w_k^- d_k^- + w_k^+ d_k^+ \}$. The epsilon variant (ϵ) is a moderately small positive number greater than 0 (between 0.02 or 0.10). The small scale of the numbers employed in the mode justifies the assumed range. The assumed " ϵ ", the epsilon, was small enough not to substantially affect the optimal value of the z_k , but large enough to ensure a Pareto optimality solution. The model utilized an epsilon value of 0.05. To fit into a linear programming optimizer structure, D was defined implicitly by adding an additional decision variable and constraint as follows:

$$D \geq w_k^- d_k^- + w_k^+ d_k^+ \quad \text{Equation 21}$$

for each $k = 1, \dots, K$.

The augmented Chebychev GP technique discussed above was applied to the energy planning problem with a total of 10 goals (g_k). As a starting point, the study used ideals goals, and these were obtained from the performance matrix in Table 10. Because the word performance matrix is easily comprehended by non-professional users of the model, it is used interchangeably with the term pay off table.. The goals for the augmented Chebychev GP technique were thus stated as follows:

$$\begin{array}{llll} g_1 = 6620.06 & g_2 = 5784.08 & g_3 = 6082.02 & g_4 = 6304.57 \\ g_5 = 1.20 & g_6 = 1.15 & g_7 = 1.15 & g_8 = 238.43 \\ & g_9 = 235.11 & g_{10} = 242.67 & \end{array}$$

We discussed the additional steps necessary to expand standard linear programming into the augmented Chebychev GP form for the energy planning problem earlier in Section 5.3.1. The augmented Chebychev GP formulation designed for the study, thus, sought to minimize $\max_{k=1}^{10} w_k d_k + \epsilon \sum_{k=1}^{10} w_k d_k$ for $\epsilon > 0$. As discussed in Section 5.3.1, for the study, a new D variable (an adjustable cell, cell F57 in the Ms Excel spreadsheet) was introduced to deal with non-linearity with an additional constraint now formulated as:

$$D \geq w_k d_k \quad \text{for } k = 1, \dots, 10. \quad \text{Equation 22}$$

The final objective function for the linear programming procedure to implement the augmented Chebychev GP metric for the energy access problem with the new D was thus formulated as:

$$z_1 = \sum_{j=1}^n Y_j K_j \quad \text{Equation 23}$$

$$z_{2k} = \sum_i \sum_j X_{ijk} R_{ijk} \quad \text{Equation 24}$$

$$z_{3k} = \sum_i \sum_j X_{ijk} D_{ijk} \quad \text{Equation 25}$$

$$z_{4k} = \sum_i \sum_j X_{ijk} E_{ijk} \quad \text{Equation 26}$$

$$\text{Minimise } D + \epsilon \sum_{k=1}^{10} w_k d_k \quad \text{Equation 27}$$

for $k = 1, \dots, 10$.

Subject to the following constraints:

Capacity constraint: $\sum_i X_{ijk} \leq Y_j$ for all j and for each scenario k .

Demand constraint: $\sum_j X_{ijk} \geq \text{demand for use } i \text{ under scenario } k$ for all i and k .

The above linear programming code was applied to the energy access problem the results are discussed in the next section.

6.4 Solution using goal programming

The problem was solved using Microsoft Excel with the Open Solver add-in (Mason, 2012), where the optimal solution was obtained. Table 11 presents a summary of the solution obtained for all objectives.

Table 11: Optimal solution

Objectives being minimised	Description	Value obtained	Goal (ideal value)
$z_{(1)}$	Minimise upfront expenditure	20 462.05	6 620.06
$z_{(2)}$	Minimise running costs	11 663.75	5 784.08
$z_{(3)}$	Minimise running costs	11 510.12	6 082.02
$z_{(4)}$	Minimise running costs	12 647.67	6 304.57
$z_{(5)}$	Minimise drudgery (z_{31})	12.34	1.20
$z_{(6)}$	Minimise drudgery	10.54	1.15
$z_{(7)}$	Minimise drudgery	10.54	1.15
$z_{(8)}$	Minimise emissions/HAP	262.53	238.43
$z_{(9)}$	Minimise emissions/HAP	281.91	235.11
$z_{(10)}$	Minimise emissions/HAP	308.01	242.67

Source: MOLP Model

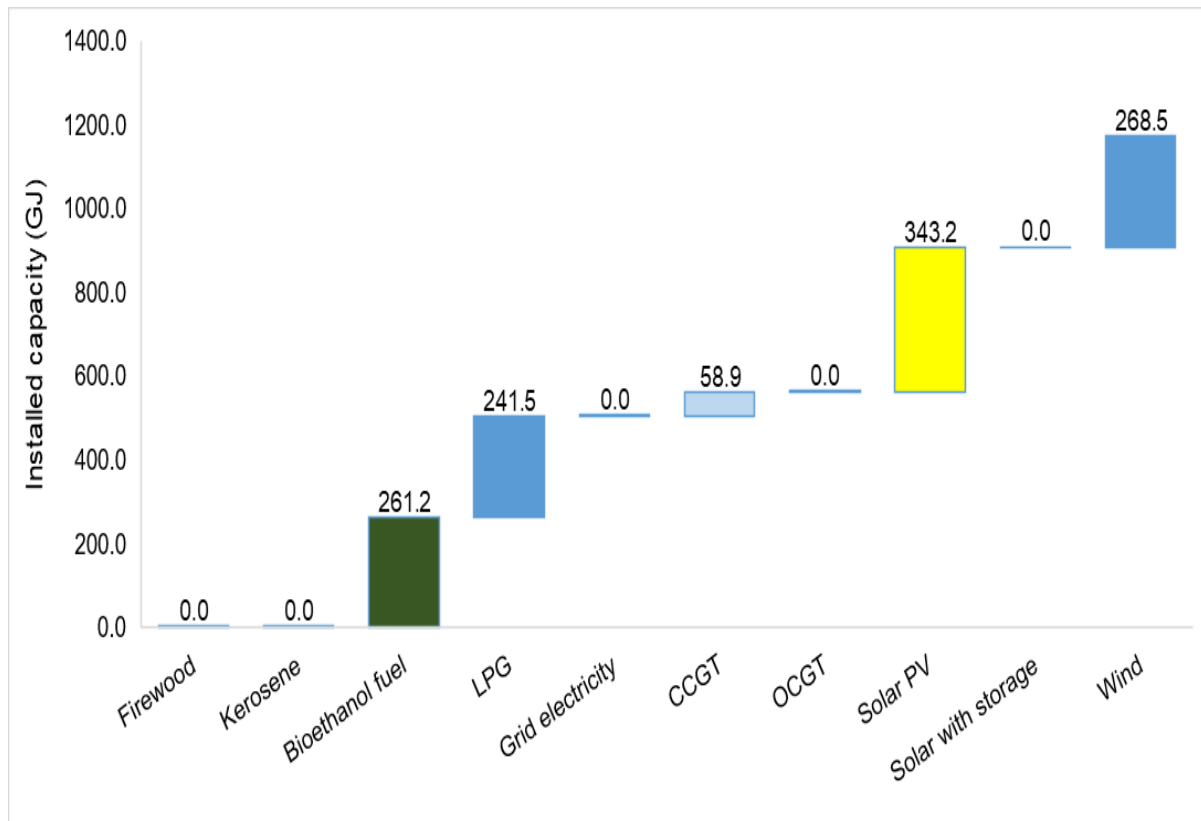
Figure 22 presents a graphic summary of the applied Chebychev GP formulation results showing the optimal solution. The results show that none of the ten objectives was fully met. Nonetheless, the model solution shows that the more important goals were closely met than the less important ones.

6.4.1 Total installed capacity

Results of the applied GP formulation show that the optimal solution would result in an installed capacity of 11.73 terajoules (TJ) for a representative community comprised of 500 households. This implied an installed capacity of 23.47 GJ per household. This would require total investment costs of approximately R20 million. As stated previously, the total installed capacity

was observed to be similar to those reported in energy demand studies reported elsewhere (Simmonds and Mammon, 1996; EMM, 2006; Winkler, 2006; CTMM, 2006; COJMM, 2007; Dalberg, 2018; Barasa, 2018). Figure 22 presents a breakdown of the installed capacities of different energy supply technologies based on the augmented Chebychev GP formulation.

Figure 22: Summary of the energy mix (installed capacity in GJ)



Source: MOLP Model

The resulting energy mix was found to be composed of electricity from a micro-grid consisting of a combination of solar PV (29.2%), wind (22.9%), and CCGT (5.0), with energy for culinary needs provided by a mix of bioethanol (22.3%) and LPG (20.6%), and none for all other technologies investigated. While less was known about liquid bioethanol in South Africa, liquid bioethanol is now increasingly viable as a cooking solution for low-income households, driven by innovations in technology and distribution (Dalberg, 2018; Barasa, 2018).

According to the results of the GP technique, in the absence of grid-based electricity, owing to challenges associated with extending the grid to dispersed communities, solar PV and wind are the feasible options for supplying micro-grid to power electrical appliances for low-income households living in rural areas. Both solar PV and wind technologies are, however, non-

dispatchable. Their non-availability during the night means that these technologies would not be resilient enough to withstand extreme weather conditions on their own.

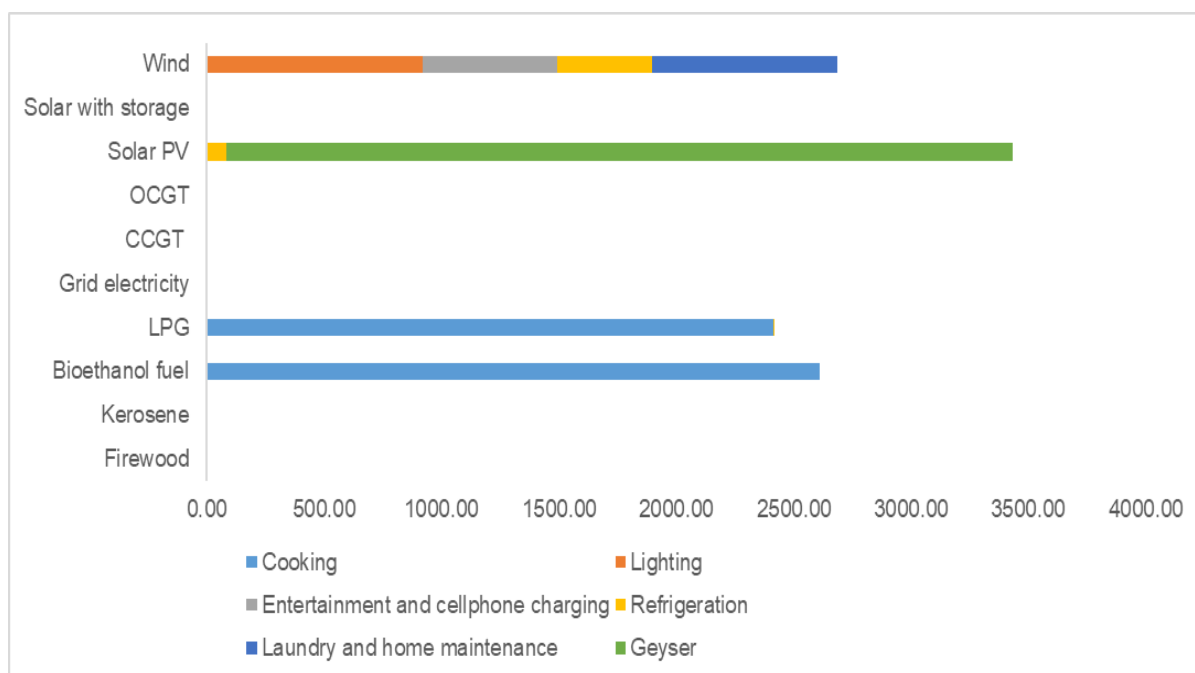
The results presented in Figure 22 show that there is no place in the energy mix for low-income households for fuels such as firewood, kerosene and technologies such as electrification through the grid electricity, diesel generation and solar with storage. For kerosene and diesel, this can be explained by the high lifecycle costs associated with fuel and high indoor pollution levels. Solar with storage also failed to make it to the energy mix on account of its high upfront costs.

The low demand for energy and corresponding low loads and the dispersed nature of rural settlements, and high infrastructure costs mean that extending the central grid is not viable in isolated rural villages. This also explains the low levels of electrification in these deep rural areas despite governments efforts to reach 100 per cent electrification. The results confirm the findings of the study by Lhendup (2008). The high lifestyle cost associated with the energy storage technologies, estimated at R 4 973.7/MWh (Gross et al., 2015), still rendered solar with storage uncompetitive when compared with comparable technologies. Bioethanol and LPG would be used to meet cooking needs. As discussed earlier, the absence of kerosene in the mix is explained by the high levels of pollution and high lifecycle fuel costs.

6.4.2 Status quo scenario

Results of the status quo scenario derived from the GP technique show that the resulting energy mix was composed of a micro-grid anchored on the solar PV and wind leveraged with bioethanol fuel and LPG. This energy mix would require R11.6 million in annual operational costs. As shown in Figure 23, the resulting energy mix under the status quo scenario shows that households would use electricity from a micro-grid of solar PV (38.8%) and wind (22.9%). Bioethanol and LPG would supply approximately 23.4% and 21.7% of the energy needed for cooking, respectively. None of the other technologies would be deployed under this scenario. This result is explained by the projected low life cycle costs associated with the bioethanol fuel and LPG, given the country's existence of LPG distribution infrastructure.

Figure 23: Status quo scenario results



Source: MOLP Model

Under this scenario, the installed capacities are slightly under-utilized. This is explained by the non-usage of CCGT (591.1 GJ) in the energy mix, given the high lifecycle costs associated with the technology. This implies that under this scenario, the economics of CCGT are not suited for deployment in low-income communities under the prevailing circumstances. What is particularly interesting to discuss from the results of the analysis is the absence of firewood in the energy mix. The analysis reveals that firewood contributes nothing under the status quo scenario and to the overall energy mix. In reality, however, as observed in literature, firewood will continue to be relied upon among the poorest. This finding contradicts what has been strongly argued in literature (Davis, 1998; Goldemberg, 2000; Thom, 2000; Gaunt, 2005; Madubansi and Shackleton, 2006; Matsika et al., 2013, and Shackleton, 2017). The study, therefore, concludes that bearing in mind that many households in rural areas collect firewood for free, firewood will remain the cheapest and most preferred energy source for cooking among the poorest of the poor.

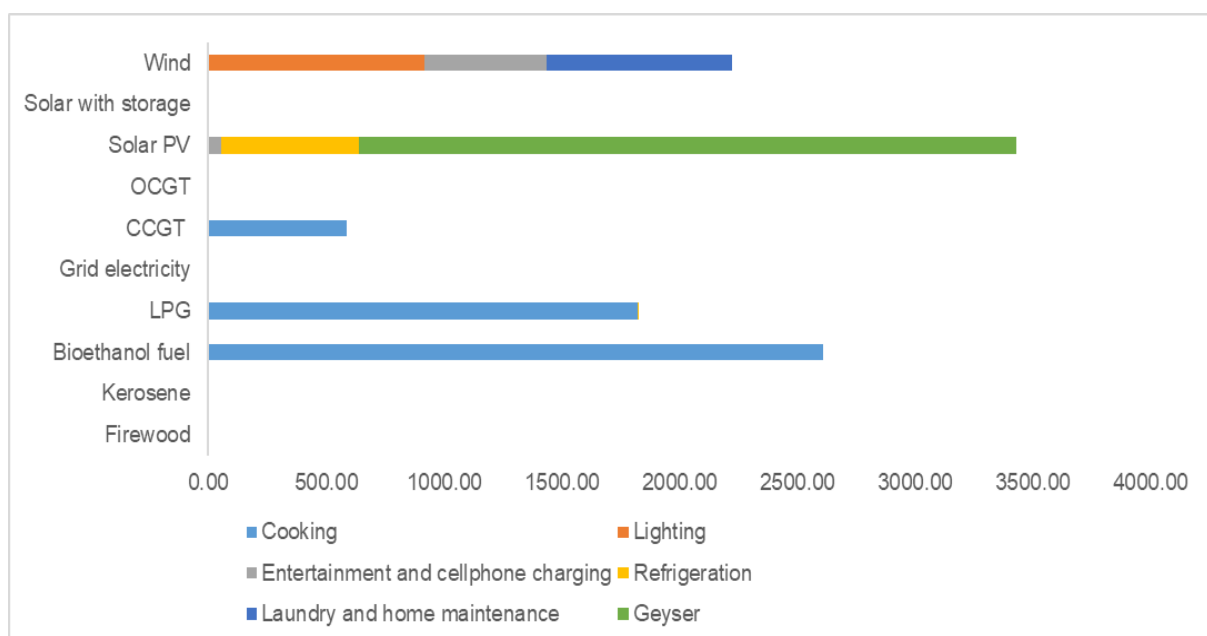
The price of firewood remains below the relative to the price of potential substitute fuels. Nonetheless, firewood would be comparatively expensive if the cost of labour and health impacts were included in the price. In terms of policy implications, what the results of the study unravelled was that in cases where households may not be able to displace firewood fully,

there was an opportunity to enhance the role of fuelwood in the short term by educating households about sustainable extraction and use of firewood wood.

6.4.3 Warmer and dry climate scenario results

As illustrated in Figure 24, the resulting energy mix under the warmer and dry climate scenario shows that households would use electricity from a micro-grid made up of solar PV (32.1%), wind (20.8%) and CCGT (5.5%) and. Bioethanol and LPG would supply approximately 24.4% and 17.1% of the energy needed for cooking, respectively. None of the other technologies would be deployed under this scenario. This energy mix would require R11.5 million in annual operational costs. This amount is similar to the required operational costs under the status quo scenario.

Figure 24: Warmer and dry climate scenario results



Source: MOLP Model

Under this scenario, the installed capacities are under-utilized. This is explained by the lower utilisation of LPG (589.1 GJ) and wind (461.2GJ) also owing to high life-cycle costs for LPG and the high upfront costs associated with the end technology. This implies that under this scenario, the economics of LPG and wind energy supply technologies are not suited for deployment in warmer and dry climatic conditions.

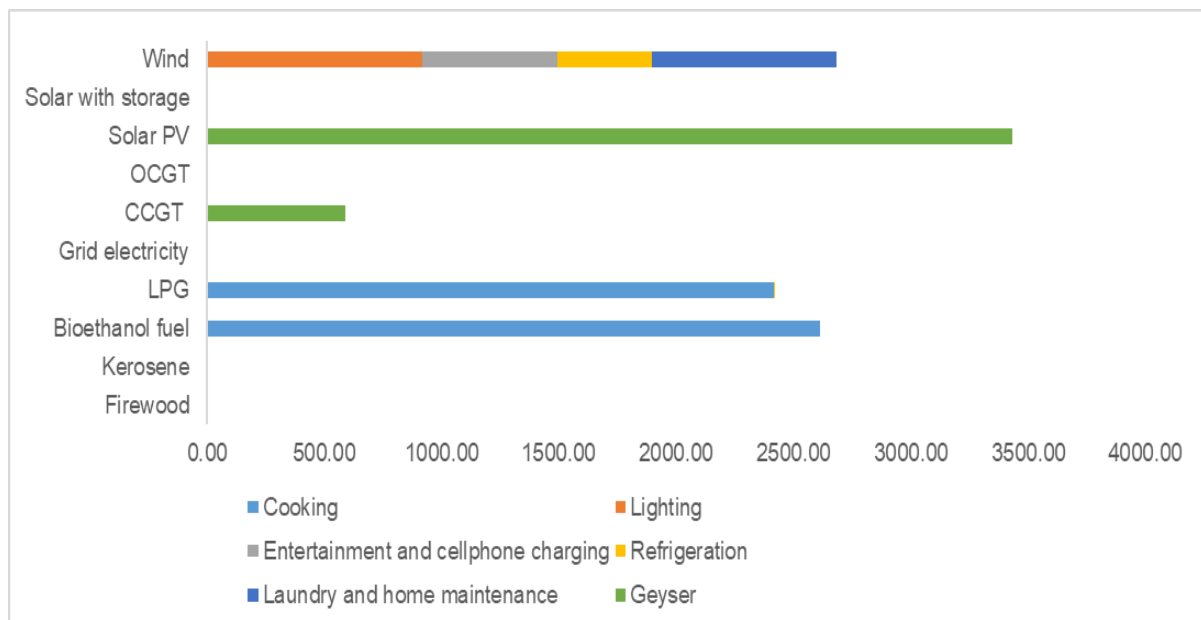
A sustained El Niño event would result in overall increases in temperature and a net decrease in energy demand. The results of the analysis under this scenario are not different from the status quo scenario except that CCGT was added into the energy mix to address the

limitations associated with solar PV and wind. The results of this study are explained by the increased energy demand and the benefits associated with bioethanol fuel ahead of firewood. Firewood has high levels of pollutants relative to bioethanol. Bioethanol fuel has relatedly low upfront costs and is less polluting when compared with other technologies and requires less time for collecting fuels when compared with firewood.

6.4.4 Cold and wet climate scenario results

A sustained La Niña event would result in an overall decrease in temperature, resulting in a net increase in energy demand, especially in winter. This phenomenon that has been observed in South Africa over the past decades. Figure 25 presents a summary of the resulting energy mix under this scenario.

Figure 25: Cold and wet climate scenario results



Source: MOLP Model

Under the cold and wet climate scenario, households would use a combination of bioethanol fuel (22.3%) and LPG (20.6%) for cooking. A micro-grid comprised of wind (22.9%), solar PV (29.2%) and CCGT (5%) would be used for powering electrical appliances, lighting and water heating (geyser). None of the other technologies would be deployed under the cold and wet climate scenario.

The installed capacities are optimally utilised under the cold and wet climate scenario. In other words, all of the installed capacity is utilised. The installed capacity is explained by a constant

energy demand profile which implies that all the installed capacity is utilised both during the day and at night. This implies that under this scenario, the economics of all the energy supply technologies in the mix is suited for deployment in cold and wet climatic conditions.

The high proportions of solar PV, wind, bioethanol, and LPG fuel in the resulting energy mix comprising clean energy technologies were similar to the results achieved under the two preceding scenarios. This energy mix would require R12.2 million in annual operational costs. This amount is higher than operational costs under the status quo and the wet and dry climate scenarios. As argued earlier, the high proportions of solar and wind in the energy mix were explained largely by their better performance in terms of full lifecycle costs (no fuel costs), less time is needed, and the technologies are regarded as non-polluting and therefore clean. Solar and wind technologies are, however, widely considered to be expensive sources of energy .

From further consultations with the panel of stakeholders, it was clear that promoting solar energy supply among poor communities would not garner enough support from either government or political actors. The prevailing perception was that solar and wind technologies are considered to be expensive sources of energy from a capital cost perspective. The government and political actors would still prefer to expand the national electricity grid.

While technologies based on grid electricity and LPG fuels could play a role in addressing the energy access problem among low-income communities, they face significant demand and supply barriers. Demand barriers for grid electricity stem from the non-affordability of electrical appliances. Similarly, supply chain barriers for LPG stem from the very complicated supply chain. The price of LPG is affected by exchange rates, taxes and distribution costs. Higher overall lifecycle costs render central grid and technologies based on diesel generation uncompetitive based on the GP formulation. Wind technology could also play a role in the future than it currently does if the required upfront capital costs continue to follow a downward trajectory, as observed over the past decade .

In terms of policy implications, this study's results advance the hypothesis that there is an ample opportunity to enhance the role of solar and bioethanol energy by developing an enabling policy framework and enabling regulatory environment for the development of a bioethanol sector leveraged on micro-grids anchored on solar and wind power in remote rural areas. According to Dalberg (2018), bioethanol has the potential to create formal, taxable domestic jobs in the value chain, including generating income for smallholder farmers. The next section discusses the results obtained from the sensitivity analysis conducted to test the impact of altering some of the model input variables.

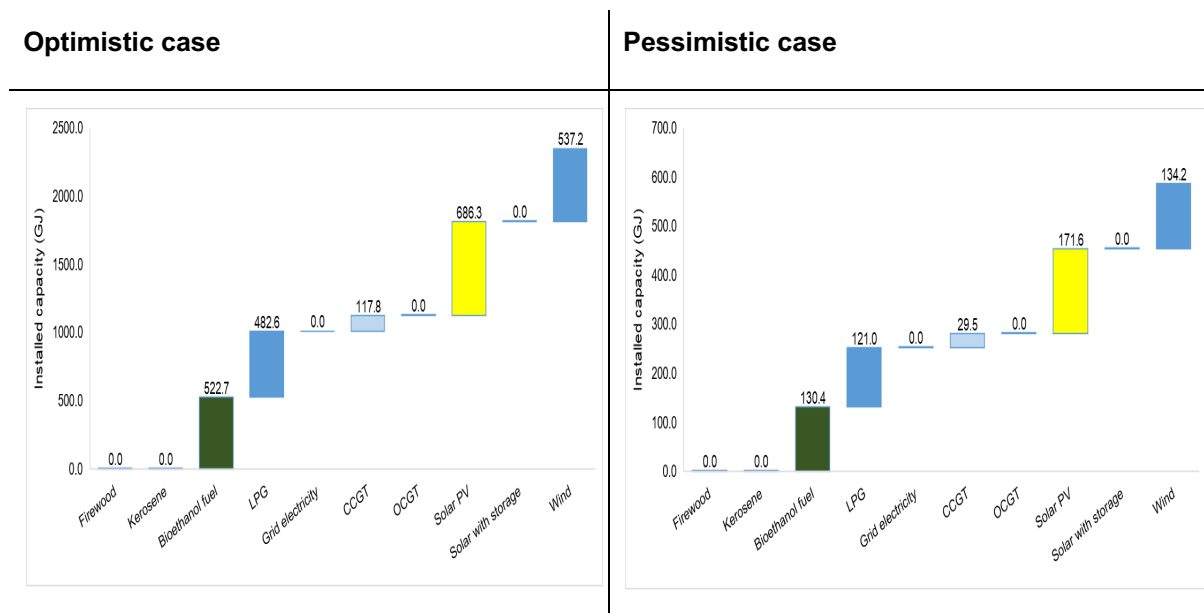
6.5 Sensitivity analysis

The model's robustness to changes in parameters and the results obtained were tested using sensitivity analysis. Sensitivity analysis was used to stress measure the effect of modifying capital, fuel costs, operational expenses, and energy consumption on the outputs of the GP model. . Costs were set to double under the pessimistic case. Costs were reduced by half under the optimistic case. By the same token, energy demand was set to double under the optimistic case and fall by half under the pessimistic case. Figure 25 and Figure 26 present the results of the sensitivity analysis. Apart from increased and decreased installed capacities, the results showed that if costs and demand were adjusted, the energy mix would still reflect those obtained in the case of solar with storage, wind, and bioethanol.

6.5.1 Total installed capacity

Results of the applied GP formulation show that the optimal solution would result in an installed capacity of 23.46 TJ and 5.8TJ under the optimistic and pessimistic cases, respectively, for the study's representative community. Figure 26 presents a breakdown of the installed capacities of different energy supply technologies based on the Chebychev GP formulation under the two different sensitivity analysis cases.

Figure 26: Summary of the energy mix: sensitivity analysis (installed capacity in GJ)



Source: MOLP Model

Consistent with the results obtained in the GP formulation above, the resulting energy mix was dominated by solar PV, wind, CCGT, bioethanol and LPG under both the optimistic and

pessimistic cases with the only exception being that, as expected, demand was higher under the optimistic case and lower under the pessimistic case.

The consistency in results obtained from the sensitivity analysis indicates the model's robustness. Despite varying parameters such as costs and demand for the different technologies, the results obtained still mirrored those under the GP formulation. Similar to results obtained under the base case, the sensitivity analysis results presented in Figure 26 confirm that there was no place in the energy mix for low-income households for technologies such as electricity through the grid electricity.

In terms of policy implications, this study's results advance the hypothesis that by altering, even on the extremes, lifecycle costs, time requirements and pollution levels of different technologies, there remains an ample opportunity for planners to increase the role of solar and bioethanol energy as core sources of energy among the poor. As previously noted, this will be achieved by developing an enabling policy and regulatory environment for the development of a bioethanol sector for the provision of thermal energy for cooking. This should be augmented by micro-grids anchored on solar for meeting the electrical needs of communities living in remote rural areas.

6.5.2 Informal urban settlements

As already mentioned in Chapter 2, energy consumption patterns in informal settlements mirror those in rural areas Nabudere (2006). Nabudere (2006) also added that the term rural area should not be associated with physical geographical localities as doing so shrouds the understanding of poverty and inequality in the country. This implies that policy interventions aimed at reducing energy poverty among the poor should be limited to isolated rural villages and be extended to informal urban settlements. A separate scenario exploring feasible energy supply options for informal urban areas was also incorporated into the Chebychev GP model. An informal urban area is defined as an illegal settlement lacking one or more of the following conditions: access to energy, water, sanitation, sufficient living area, housing durability and security of tenure, as adopted in the SDG 11.

This external scenario was also elicited as part of the second round of the strategic dialogues, which were conducted with the panel of experts and community representatives. The panel of experts and community representatives were asked the question *"Do you agree with the hypothesis that energy consumption patterns in informal settlements mirror those in rural areas and policies aimed at reducing energy and poverty, in general, should not discriminate communities living in informal urban settlements?"*. Feedback was collected, collated and

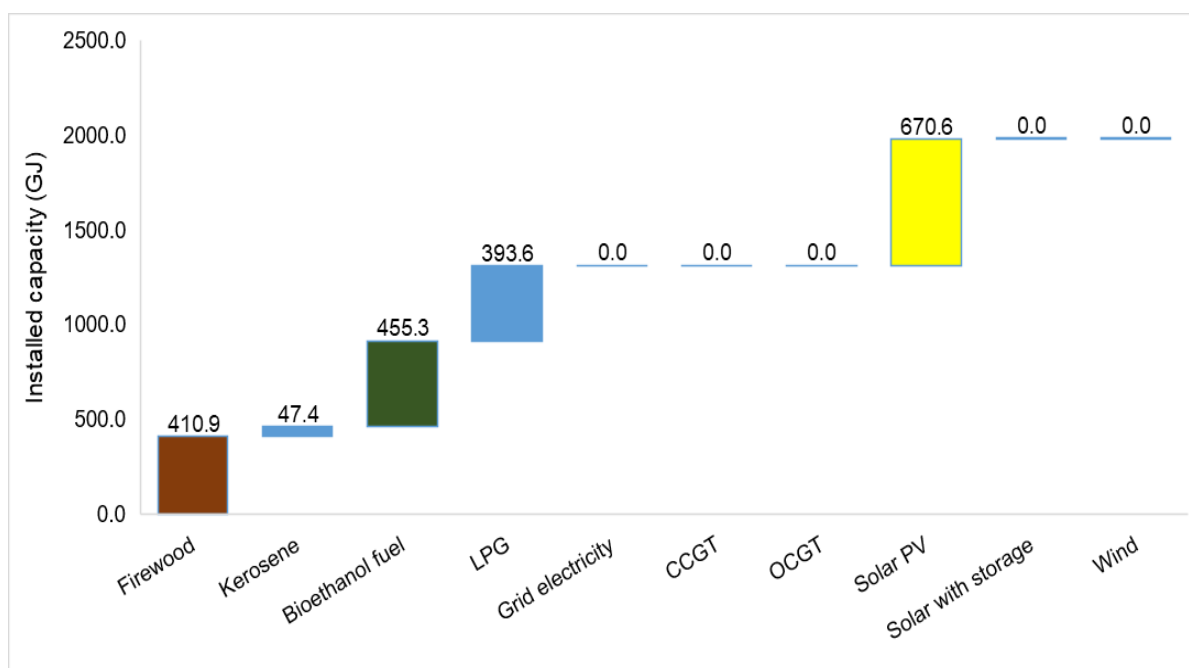
reviewed iteratively with the panel of experts. The experts agreed on pursuing the informal urban settlement scenario only.

Informal urban settlements GP model results

The applied GP formulation results for the informal urban settlements scenario showed that the optimal solution would result in an installed capacity of 19.7 TJ for a representative community comprised of 500 households. This implies an installed capacity of 39.5 GJ per household. Figure 27 presents a breakdown of the installed capacities of different energy supply technologies based on the augmented Chebychev GP formulation for the informal urban settlements scenario.

The resulting energy mix comprised a micro-grid powered by solar PV (33.9%) leveraged by bioethanol fuel (23%, firewood (20.8%), LPG (19.9%) and kerosene (2.4%). This result was explained by the projected low life cycle costs associated with solar PV, bioethanol and LPG fuels compared with solar with storage. As argued earlier, the high lifecycle cost associated with the energy storage technologies would still render the technology uncompetitive when compared with comparable technologies.

Figure 27: Summary of the energy mix (informal urban area, installed capacity in GJ)



Source: MOLP Model

In terms of usage, results obtained from the study indicate that solar PV and LPG would be used for meeting electrical power needs, including refrigeration, while a combination of bioethanol, firewood, LPG and kerosene would be used for cooking. The choice between bioethanol and LPG for cooking would be influenced largely by the economic and supply chain topographies of where these technologies would be deployed.

According to the results of the analysis, in the absence of grid-based electricity, owing to challenges associated with extending the grid to informal urban settlements, solar PV was found to be the only feasible option for supplying micro-grid to power electrical appliances for low-income households living in these areas. The results also confirm the energy ladder postulate that as household income rises, they tend to replace rudimentary energy with modern energy sources. The opposite was confirmed to be equally true. This argument is confirmed by the return of kerosene in the energy mix under the pessimistic scenario. The results indicated that faced with limitations and as incomes shrink and energy demand falls, poor households revert to low-cost energy sources such as kerosene and firewood. This finding also confirms what has been observed in other studies (Dube et al., 2020; Thomson Reuters Foundation, 2021).

According to Dube et al. (2020), weak infrastructure, erratic supply, maintenance issues and the unaffordable cost of electricity in the face of unemployment and low incomes in Zimbabwe resulted in increased use of firewood, leading to deforestation. Similarly, and more recently, in early 2021, dwindling family budgets due to the global coronavirus pandemic sparked a surge in firewood use in informal urban settlements in Kenya in 2021, according to a report by Thomson Reuters Foundation (Thomson Reuters Foundation, 2021). As already mentioned, the situation can be improved by introducing bioethanol fuel into the mix through government-supported programmes. This can be supplemented by sustainable firewood extraction and utilisation in the short term.

In terms of policy implications, the results of the study showed that, indeed, energy consumption patterns in these areas mirror those in rural areas. This finding means that, first, energy planners in South Africa should not limit the term “rural area” to physical geographical localities. Instead, the definition should be extended to include the shanty towns and informal urban areas. Secondly, the findings of this study also imply that when designing intervention programmes aimed at benefiting poor rural households, these initiatives should also include solutions for underprivileged homes located in informal urban settlements. Recent data from the United Nations Human Settlements Programme show that as of 2018, approximately 25.6

million South Africans live in slums across the country (World Bank Group, 2021). These slums are concentrated in Gauteng, the Western Cape, North-West and the Eastern Cape. Exhibit 2 shows a typical informal urban dwelling in South Africa.

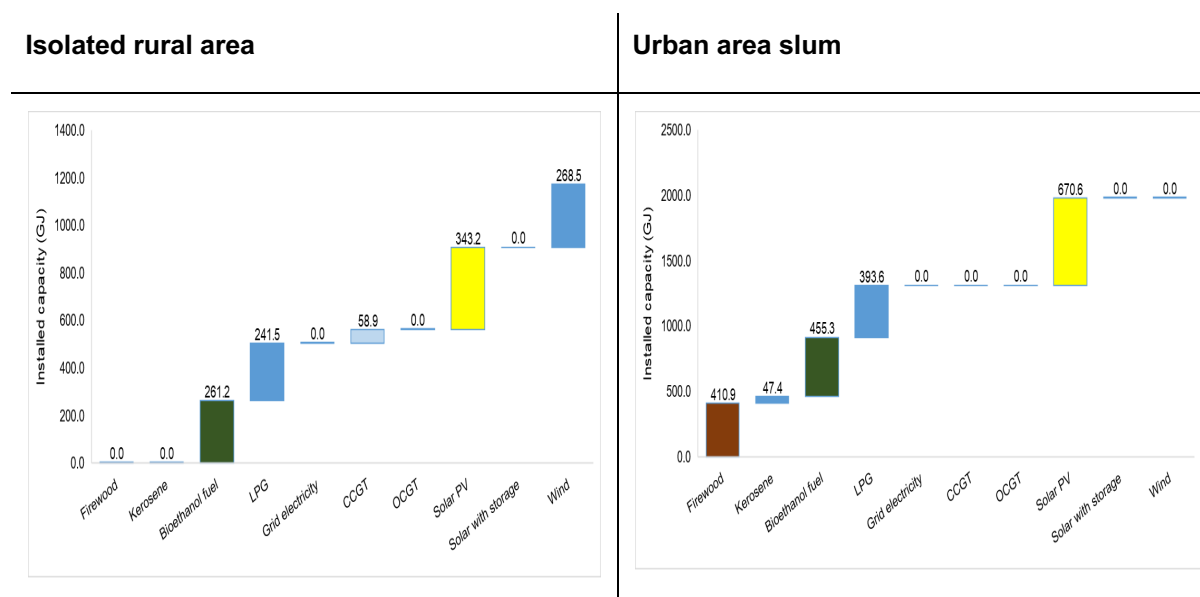
Exhibit 2: Informal settlements in South Africa



Source: Flickr (2021)

The augmented Chebychev GP model developed for the study was useful under differing circumstances. Figure 28 presents a side-by-side comparison of the installed capacities (Y variables) for isolated rural areas and the informal urban areas scenarios. Notable differences between the two circumstances are the presence of firewood under the informal urban area scenario and the absence of wind under the same scenario. Solar is also more pronounced under the informal urban area scenario. Under the isolated rural area scenario, users of the model should include all energy supply technologies. Under the informal urban settlements scenario, users of the model should exclude certain technologies such as wind and grid electricity, given the technical and regulatory limitations placed on deploying such technologies.

Figure 28: Comparison of the installed capacities (installed capacity in GJ)



Source: MOLP Model

In cases where the ban on the connection of informal households to the national grid is lifted, the informal urban area scenario should then also include grid electricity, albeit with higher energy demand than the isolated rural areas scenarios. Additionally, with an ever-increasing informal urban area population and the expansion of informal settlements in South Africa, energy planners would need to consider this increasing population when finding energy access solutions using the developed model.

6.6 Implications for practice

The author's work in building the augmented Chebychev GP model and applying it to a hypothetical energy access problem has practical implications. The next three sections summarise the implications for practice.

6.6.1 Adopting the augmented GP model energy access problems

Results obtained from the study supports the continuing emphasis on the suitability of the GP technique to optimising objectives relating to competing activities in energy planning and subject to resource availability through the use of mathematical programming. Assuming a single objective, an ideal approach would have been the application of simple linear programming. The single objective limitation of linear programming models has been identified as a drawback of their use. This is synonymous with some of the limitations highlighted in Chapter 4 in relation to the widely used CBA technique in the public sector.

The shortcoming of single-objective linear programming models was overcome in this present study by developing multiple objective functions integrated into linear programming, providing the ability to incorporate distinct and even conflicting objectives in examining energy planning issues under three different scenarios.

Decision-makers in the public policy-making environment confronted with large-scale problems can make use of the GP model developed in this study. This is because the GP model developed for the study was designed to handle problems with a very large number of alternatives and to narrow the search for fewer options before other techniques can be applied to further assess the options. GP is also useful for examining the trade-offs between objectives, incorporating activities and constraints within the model and enabling decision-maker weighting in use.

The author is not aware of any literature where the question of seeking the optimal energy mix with poverty considerations has been considered. In the author's opinion, this is the main novelty of the present study, along with the application of GP to the question of the optimal energy mix for low-income households in a developing country.

6.6.2 Utilising the model developed under the different scenarios

Although the results of the study are based on a hypothetical example and represent a theoretical decision situation and the three different scenarios considered are also limited to three hypothetical situations, the model, however, presents an opportunity for a real-world application. Empirical applications can be even more complex. The author, therefore, found it worthwhile to provide further guidance on the modalities to follow when implementing the model under different sensitivity analysis situations but in a real-life environment.

The model developed enabled interrogation and provides a platform for understanding how changes in any of its technical variables could change the overall situation. For example, after examining the output presented in Figure 28 and appreciating that the solutions obtained under the two different scenarios were different. Urbanization is a major demographic driver of energy demand. The amounts and types of energy used by rural and urban households will continue to differ significantly.

The model could be used to assess the strategies needed to change the urban area slum solution to make it aligned with the national and global goals of eradicating poverty and the use of polluting fuels such as kerosene and fuelwood. This could be achieved by improving the logistics needed to ensure the availability of LPG and bioethanol fuel together with the

financial incentives needed to make bioethanol fuel cost-effective. As the Government provides a fiscal subsidy, kerosene is sold for less than international market prices. The same fiscal subsidy can be redirected to cleaner fuels such as LPG and bioethanol fuel.

In line with the study's findings on users' reluctance to adopt modern energy sources for cultural reasons, especially in isolated rural areas, the study suggests that additional approaches are needed to ensure sustainable collecting and use of firewood. These approaches include promoting the use of efficient cookstoves, promoting afforestation at a community level and the design of modern cooking systems that mirror traditional cooking methods. The study proposes that more thought should be given to the technical design and user acceptability of efficient cookstoves in both urban and rural areas.

The study solution for the isolated rural areas scenario may be dismissed as artefactual when, in fact, they point to real areas of concern. For example, given the lack of awareness in rural areas about the benefits of LPG (time-saving, health and environmental), LPG is still perceived as unsafe. Low literacy levels are also another obstacle. Illiterate people tend to prefer their traditional practices and be resistant to change. Therefore, efforts should be invested in education and awareness campaigns to ensure that communities are informed about the benefits of clean fuels and sustainable use of fuelwood. Through accredited community health workers, the health sector is one avenue available to channel educational information on clean fuels and health.

6.6.3 What do the decision-makers learn about their goals?

The study notes that the public policy-making environment is increasingly becoming complicated by the emergence of competing goals. As observed in this study, these goals range from political, economic, social, technological, environmental and legal goals. The current challenges of global economic instability coming from the 2019 coronavirus pandemic (Covid-19) and the climate change discussion exemplify this. Trade-offs and synergies are often unclear, and contributions by different stakeholders to the challenges faced may be unequal. The study makes the case that, because of the interdependencies of goals in energy planning, decision-makers must use strategic approaches and procedures that address all of the goals simultaneously to find the best solutions.

The study established the goal of minimising upfront capital costs is an important one. The economics of energy supply technologies is evolving. For example, as shown under the three study scenarios, the cost of renewable energy technologies is improving, with reported

significant declines in the cost of manufacturing and installing some technologies such as solar and wind as technical advances materialise.

In the case of solar PV, there has been a decline of about 82% (IRENA, 2020) in the cost of generating power, with every doubling in installed capacity over the last few decades. Wind energy has also benefitted from technological improvements and turbine scaling over the past decade. Additional reductions in costs are anticipated as these technologies undergo further technical learning and improvements in the manufacturing processes and large scale production. These developments contrast with the rising costs for conventional energy supply technologies that do not follow learning curves. This development suggests that the price difference between conventional and renewable energy technologies will become even larger in the future. These developments need to be factored into policies made today. However, decision-makers should be aware that significant up-scaling and deployment of renewable technologies is critical for the realisation of the expected cost reductions.

The study observed that the minimisation of the operational lifecycle costs is also an equally important goal. Renewable energy technologies are associated with near-zero fuel costs making them cheaper from a lifecycle cost perspective. As highlighted above, this contrasts with rising costs for conventional energy supply systems, which are largely affected by rising market-determined prices of fossil-based fuels (such as coal, gas etc.). Consequently, it is not surprising that the resulting optimised energy mix from the GP model which comprised of electricity from a micro-grid comprised of a combination of solar PV, wind and bioethanol and LPG and none for all other technologies considered.

Any intervention that results in high recurring energy bills will inevitably push the poor into further poverty. This will result in either the government having to step in to cover the bills through fiscal transfers or the low utilisation of the installed systems rendering the intervention obsolete. The study, therefore, puts forward the notion that when making investment decisions aimed at extricating the poor from further poverty, the costs of running the installed system should be lower for the beneficiary to benefit from the intervention fully. Low electricity usage among low-income families with access to grid electricity typifies the notion. Apart from electricity bills, beneficiaries are expected to buy electrical appliances, which are usually beyond the reach of many given the low income levels (Bhorat et al., 2012; Stats SA, 2019).

In addition to costs, other technology-specific goals (such as the time needed to collect fuels and maintain systems and environmental pollution) need to be factored in when making energy access investment decisions. While the minimisation of drudgery is a key consideration

for reducing poverty as spending less time on uneconomic activities has the direct consequences of increasing the amount of time available for productive activities.

Collecting fuels is commonly considered a women's and young girls' duty (Dovie et al., 2004; Howells et al., 2005; Matinga and Annegarn, 2013). This has meant that women and young girls remain in the throes of poverty, given the lack of access to education and productive and income-generating employment activities (Kaygusuz, 2010). Integrating drudgery minimisation in energy planning among the poor is one of the avenues available for fighting gender inequality in South Africa. Gender issues still plague South Africa. According to the World Economic Forum's Gender Gap Index, South Africa ranks 19 out of 149 countries (Schwab et al., 2017), 2018).

Related to drudgery, decision-makers should integrate environmental goals when crafting energy access interventions. Environmental considerations include decisions concerning the reduction of household air pollution. The present study dealt with an energy access decision to substitute high polluting fuels with cleaner fuels to promote healthy living among the poor. Low-income communities can benefit both directly and indirectly by embracing the notion of environmental management. A direct benefit is the reduction of indoor household air pollution, which leads to better health outcomes and fewer hospitalizations. An indirect advantage is the decrease of social expenses such as environmental degradation and natural resource depletion, as well as the establishment of an eco-friendly image.

For the most part, the study showed that there are strong linkages and trade-offs between goals. Synergies would need to be exploited further to maximise the quality of the decisions to be made, while trade-offs would need to be handled in a manner that results in the development of a fully optimised portfolio. The projected declining costs of renewable energy technologies are likely to narrow the trade-offs between goals, particularly the minimisation of upfront capital costs and environmental goals that appeared at a tangent at the time of the study.

As the debate on climate change rages, ensuring access to clean energy is essentially sustainable decision-making. South Africa needs to achieve SDG 7, "ensuring access to affordable, reliable, sustainable and modern energy for all." Sustainable decision-making is, therefore an excellent example of a multicriteria decision-making process, where decisions have to be taken taking into account the goals of a range of stakeholder groups. Through sustainable investing in energy infrastructure, low-income communities can achieve economic

and social benefits. The reduction of lifecycle economic costs and indoor household air pollution means better socio-economic outcomes for the country.

6.7 Chapter conclusion

Analysis of the results based on the GP model shows that while it is cost-optimal to pursue electrification in conjunction with other short-term augmentation solutions to meet South Africa's universal electrification targets, sustainable energy access rates among low-income households located in isolated rural areas can be achieved by increasing the share of clean energy generation technologies in the energy mix.

Planners seized with formulating and implementing energy policy in South Africa are encouraged to reconfigure the current energy grant and subsidies regime in favour of interventions that result in immediate impact. For instance, instead of spending billions of rand on subsidised paraffin for indigent households, the same resources could be utilised for the deployment of bioethanol distribution infrastructure. Unlike paraffin, biofuel is cleaner and locally produced, which implies local employment creation and import substitution. Adding solar PV to the mix will help cater for the electricity needs of these indigent families.

But how should the study's "optimal portfolio" be promoted, given the associated higher initial capital costs and the need to extend access to affordable energy services? Can the final decision be based on the findings of the technical assessment? An additive MAVT approach is introduced in the next chapter to address these questions for evaluating and selecting choices from the shortlist emerging from the development phase (GP model).

The augmented Chebychev GP technique was employed as a screening method, generating a small number of solutions (discrete sets) that needed to be treated in another way. The GP model was run GP on a number of occasions, each time varying goals until a smaller number of solutions were obtained. Softer criteria identified in the initial stages that may have been side-lined in the technical processes and thus could not be assessed using the augmented Chebychev GP technique were employed in the next chapter.

CHAPTER 7
EVALUATION AND SELECTION OF STRATEGIES USING THE VALUE
FUNCTION TECHNIQUE

7.0 Chapter introduction

It has been established earlier in Chapter 3, Chapter 4 and Chapter 6 that it is computationally challenging to develop optimal solutions using the GP technique alone. This is because the GP technique is better suited to dealing with quantitative criteria and is incapable of dealing with qualitative criteria. In this chapter, the MAVT is applied to evaluate the effect of incorporating qualitative criteria to the objectives used in GP analysis on energy choice among low-income households that could not be assessed using the GP technique. This chapter relates to the application of the developed framework - a GP model extended by an additive model anchored on the foundations of the MAVT technique.

7.1 Methodology

Before explaining how each step of MCDA was carried out in this research, it is important to state how the interactions between the author of this study and the panel of experts who represented decision-makers happened. The author played two roles during the modelling process: as an interviewer, he interacted with the panel of experts through one-on-one meetings where it was possible and through virtual platforms; and as a modeller, the author translated all the information provided by the panel of experts into a computational language, using the V.I.S.A GroupWare (Version 8.1 for Windows).

On the market, there are various online and offline MCDA software solutions (Belton and Stewart, 2002; Mustajoki and Marttunen, 2013; Weistroffer and Li; 2016). Several MCDA software products were chosen and evaluated for capability, adaptability, and user interface before making the software purchasing decision. Table 12 summarizes three software options currently on the market.

Table 12: MCDA Software options

Software package	Categories of decisions supported	Supplier	Usefulness to the study
HiView 3	Discrete choice problems	Catalyze Ltd	Effective for group decision making, such as decision conferences and for individual decisions

Software package	Categories of decisions supported	Supplier	Usefulness to the study
V I S A ²⁵	Discrete choice problems	SIMUL8 Corp	VISA is entirely web based and is available free for academic use.
DEFINITE	Discrete choice problems (with emphasis on impact studies)	Institute for Environmental Studies	Software packages specifically developed for use in public sector impact studies are available.

Source: Belton and Stewart (2002), Mustajoki and Marttunen (2013), Weistroffer (2016)

Belton and Stewart (2002), Mustajoki and Marttunen (2013), and, more recently, Weistroffer and Li provided guidelines for software selection (2016). The V.I.S.A groupware suite was used in the study. This software package received a higher ranking in the selection criteria since it is free for academic use, simple to install, and does not require internet connectivity. Furthermore, the software programme was chosen since it was relatively simple to implement and could accommodate several projects.

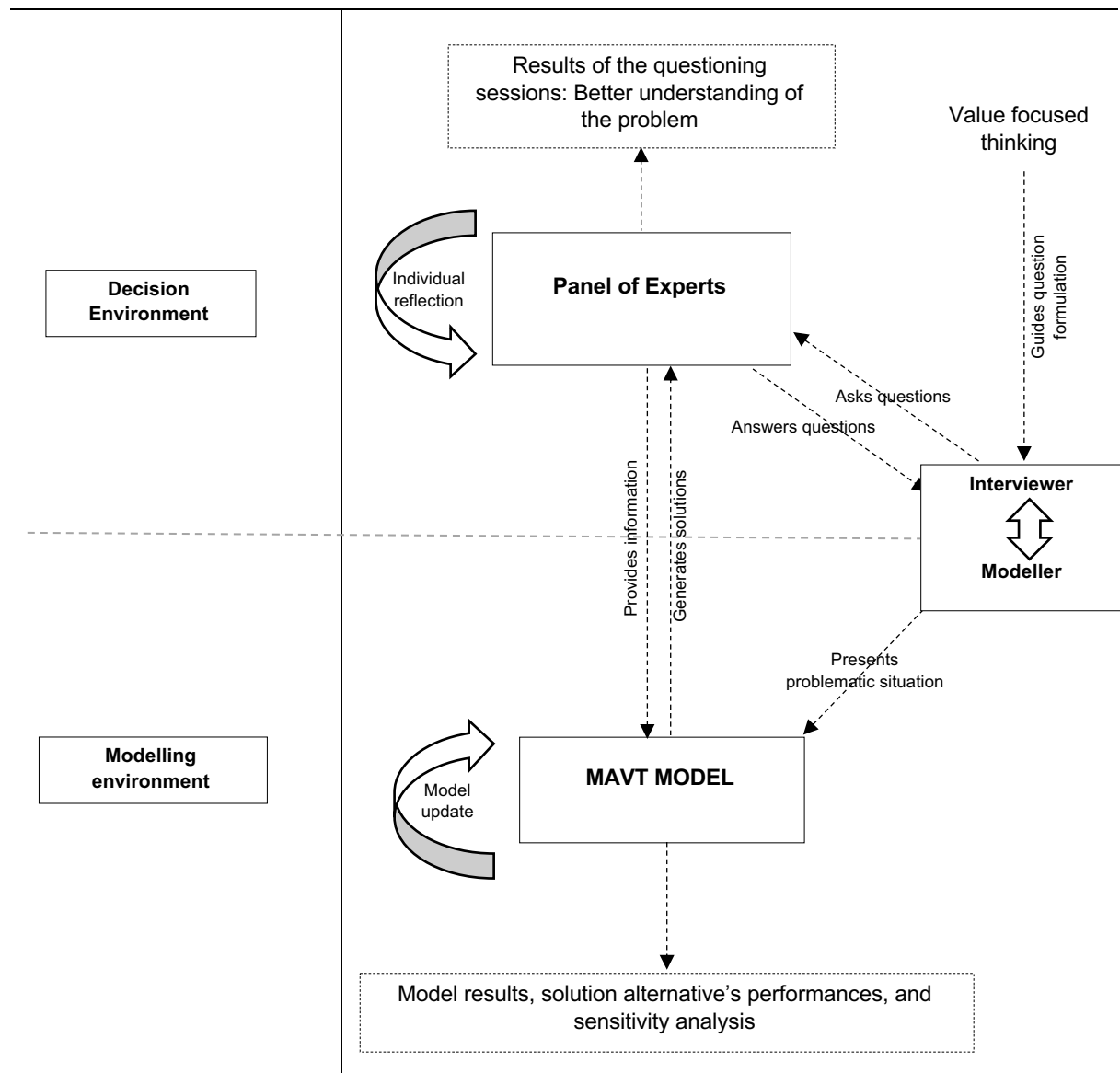
Most of the practical use of the V.I.S.A groupware is about groups deciding by reaching a consensus. The software allows the user to build a decision tree, set up alternatives, score each alternative and apply weights to criteria. The system computed the ratio scale priorities for elements on criteria using input data.

The MAVT model was implemented in two parallel framework contexts, as previously stated in Chapter 3, Section 3.1. The first environment involved the interviewer leading talks and brainstorming sessions using the value-focused thinking technique (VFT). VFT is a decision science theory introduced by Keeney (1992) based on the concept of shifting stakeholder values. VFT includes a technique for identifying objectives. This procedure typically includes discussions with key decision-makers and stakeholders. The second environment is comprised of the modelling process. Figure 29 illustrates both environments, showing the author's roles as interviewer and modeller. As shown in Figure 29, the MCDA framework applied was divided into three modelling phases.

²⁵ Visual Interactive Sensitivity Analysis

Given the time and financial resource constraints, there was limited access to real decision-makers. The study, therefore, relied on the panel of experts constituted under the technical evaluation phase (GP model). The panel represented decision-makers. To complement the panel members' views and augment brainstorming steps, the study also made use of information available on websites of leading research institutes²⁶ and humanitarian organisations²⁷ and academic literature.

Figure 29: Discussion and modelling environments



Adapted from Franco and Montibeller (2010)

²⁶ www.epri.com; www.csir.co.za; www.erc.uct.ac.za

²⁷ www.cleancookingalliance.org; www.seforall.org

7.1.1 Stakeholders

The problem was defined during the first phase of the modelling environment. Before engagements with the panel of experts, an extensive literature review was conducted to understand the important energy access concepts and issues among low-income households. The panel members were then requested first to validate and add new groups that could be affected by the decision problem in addition to those identified in Chapter 6 (Figure 20). This process led to the identification of stakeholders to the problem. The stakeholders were classified into different groups discussed in Section 6.1.1, namely decision-makers, impacted groups and influencers (Figure 20).

7.1.2 Attributes and indicators

Mathematical structuring and stakeholder objectives were elucidated in the second phase using brainstorming techniques. Stakeholders, represented by the panel of experts discussed in the previous chapter, were instrumental in defining the attributes employed in this routine. Goals used in the augmented Chebychev GP model were first incorporated into the MAVT framework forming a link between the two techniques. The MAVT technique incorporated softer criteria that the augmented Chebychev GP technique could not handle.

The interactive MAVT application took the form of iterative two-phased face to face, telephonic and virtual interviews. Virtual interviews were conducted using Microsoft Teams, Zoom and Google Meet. These platforms were selected for the interactive advantages which permit video and screen sharing. Refer to Appendix D for step-by-step guidance on how to use the V.I.S.A groupware package. In addition to the goals considered under the augmented Chebychev GP technique, the panel members were first requested to enumerate all objectives that they would consider when crafting energy access interventions. Objectives obtained from literature were shared with the panel members, and the participants were then requested to validate the original objectives list.

In the last steps of this phase, the panel members were requested to explain, for each objective, including goals incorporated in the augmented Chebychev GP technique and why they would consider it and its direct consequences. This led to the listing of more objectives and the identification of relationships between pairs of objectives.

Three primary criteria and fourteen sub-criteria were chosen for analysis by the panel of experts after a screening procedure utilizing the brainstorming technique. The three-parent criteria identified were the user, fuel and system criteria. Two child criteria were also selected for the user criteria. The cost child criteria under the cost-benefit criterion was chosen as:

- Investment costs (considered under the Chebychev GP technique); and
- Lifecycle operating costs (considered under the Chebychev GP technique).

The benefit sub-criteria under the cost-benefit criterion were selected as:

- Time savings (considered under the Chebychev GP technique); and
- Health benefits.

The sub-criteria under the fuel type criterion were selected as:

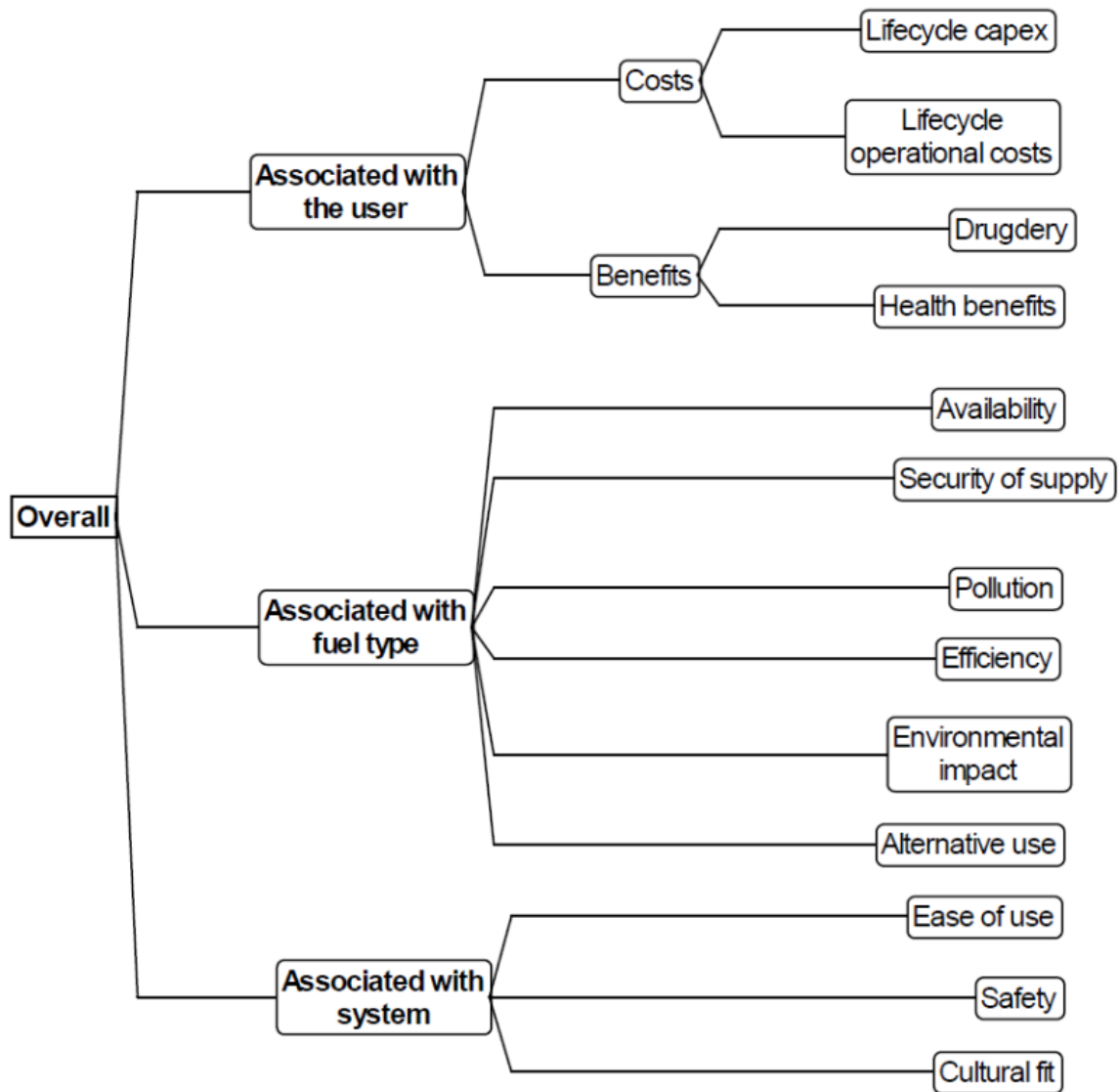
- Availability;
- Security of supply;
- Pollution (considered under the Chebychev GP technique);
- Efficiency;
- Environmental impact; and
- Alternative use.

The child criteria under the system criterion were selected as:

- Ease of use;
- Safety; and
- Cultural fit;

Using the above criteria, a value tree was constructed by the panel of experts using the network constructed by the V.I.S.A groupware, which in essence depicted mean-objectives and end-objectives. Figure 30 presents the resulting value tree of the alternative energy supply technology options.

Figure 30: Value tree



Source: V.I.S.A groupware model, study strategic dialogues

It is worthwhile noting the differences between the above-mentioned and GP objectives, reasons and potential impacts. The augmented Chebychev GP technique applied in the previous chapter only considered goals whose input variables were quantitative. The MAVT technique considered goals whose input variables were both quantitative and qualitative. As such, the MAVT technique should be viewed as an extension of the augmented Chebychev GP as it now incorporated softer criteria that were side-lined in the technical processes and thus could not be assessed using the augmented Chebychev GP technique. Table 13 presents a comparison of the augmented Chebychev GP and MAVT, and objectives highlight extensions and their impact.

Table 13: Comparison of GP and MAVT objectives

Objective	GP	MAVT	Comments
1. Maximise safety		√	Qualitative objective, in domestic environments, fuel safety is of utmost importance. Safer energy supply options are most preferred in these environments.
2. Maximise availability		√	Qualitative objective, easy access and availability of fuel impacts on energy supply choices. Easily available energy supply options are most preferred.
3. Maximise security of supply		√	Qualitative objective, security of supply also impacts energy supply choices. More secure energy supply options are most preferred.
4. Maximise alternative use		√	Qualitative objective, energy supply options with diverse use are most preferred.
5. Maximise efficiency		√	Qualitative objective, energy efficiency implies less use of energy, highly efficient energy supply options are most preferred.
6. Minimise capex	√	√	Quantitative objective whose variables incorporating lifecycle capital expenditure were considered under the GP and MAVT frameworks adopted.
7. Minimise opex	√	√	Quantitative objective whose variables incorporating lifecycle operational costs were considered under the GP and MAVT frameworks adopted.
8. Minimise environmental impact		√	Qualitative objective, environmental impacts of fuel influences energy supply choices. Energy supply options with the least impact on the environment are preferred.
9. Minimise pollution	√	√	Quantitative objective whose variables incorporating pollution impacts were considered under the GP and MAVT frameworks adopted.
10. Maximise health benefits		√	Qualitative objective, health benefits of fuel impacts on energy supply choices.

Objective	GP	MAVT	Comments
11. Maximise cultural fit		√	Qualitative objective, culturally acceptable energy supply options performed better.
12. Maximise ease of use		√	Qualitative objective, easy to use energy supply options performed better and are most preferred.
13. Minimise drudgery	√	√	Quantitative objective whose variables incorporate time spent collecting fuel and maintaining systems were considered under the GP and MAVT frameworks adopted.

Source: Study strategic dialogues

Participants were also requested to identify the most suitable and practical indicator by which the performance of each option on each of the new attributes could be measured. Table 14 presents a summary of the issues raised during strategic dialogues and the justification for the inclusion of the attributes used in the model.

Table 14: Attributes and indicators

Attribute group	Attribute	Strategic dialogue feedback summary	Justification
Technical viability	1. Safety 2. Alternative use 3. Availability 4. Security of supply 5. Efficiency	Performance and reliability are measured by (efficiency and heat values) of an energy supply technology.	Technical barriers can constrain the implementation of some technology options.
Economic viability	6. Capex 7. Opex	Economic costs (measured by investment and operating costs) to the user.	Trade-offs exist between investment costs and ongoing operating costs.
Environmental	8. Environmental impact 9. Pollution 10. Health benefits	Environmental benefits and costs (measured by Co2 emissions) to the user and society.	While feasible, some technology options can be constrained by environmental barriers.

Attribute group	Attribute	Strategic dialogue feedback summary	Justification
Social	11. Cultural fit 12. Ease of use 13. Drudgery	Social benefits and costs (measured by time spent and acceptability) to the user and society.	While feasible, some technology options are constrained by social barriers.

Source: Study strategic dialogues

Possible solutions to the problem were elaborated towards the end of the second phase. The set of alternatives were created following the VFT approach discussed earlier in Section 7.1. In addition to alternatives that emanated from the technical evaluation, the panel of experts was requested to draw up a list of alternatives that would fulfil one performance criterion at a time. Two at the same time and so on, until the number of criteria considered made it impossible to come up with solutions that would succeed in all of them. The panel of experts then screened the original list of possible alternatives. . With the pre-emptive criteria and the list of desired criteria in place, the panel identified a list of energy supply technologies that met the pre-emptive criteria and looked closest to the desired criteria.

Altogether, the ten energy supply strategies were evaluated in this routine. The policy-relevant strategies were identified as appropriate in unravelling the problem. These strategies were defined by the panel of experts and were ranked in order of the most rudimentary to the cleaner options. The selection and construction of the strategies were undertaken by the experts during the strategic dialogue sessions conducted. Table 15 and Table 16 provide summaries and technology characteristics of the ten energy supply portfolios considered for the study, with Portfolio 10 being the optimal GP model portfolio. The same input variables were used under the augmented Chebychev GP model (Table 13).

Table 15: Energy supply portfolios: rural area community

Portfolio name	Portfolio components (mix)									
	Firewood	Kerosene	Bioethanol fuel	LPG	Grid electricity	CCGT	OCGT	Solar PV	Solar with storage	Wind
Energy portfolio 1	55%	45%	0%	0%	0%	0%	0%	0%	0%	0%
Energy portfolio 2	45%	35%	5%	5%	10%	0%	0%	0%	0%	0%
Energy portfolio 3	35%	20%	15%	10%	20%	0%	0%	0%	0%	0%
Energy portfolio 4	25%	15%	10%	15%	25%	0%	0%	10%	0%	0%
Energy portfolio 5	20%	10%	20%	15%	10%	0%	0%	15%	0%	10%
Energy portfolio 6	15%	5%	15%	20%	10%	5%	5%	15%	5%	5%
Energy portfolio 7	10%	0%	10%	25%	10%	10%	10%	10%	5%	10%
Energy portfolio 8	5%	0%	10%	20%	0%	5%	5%	20%	5%	30%
Energy portfolio 9	0%	0%	5%	20%	0%	5%	0%	30%	15%	25%
Energy portfolio 10	0%	0%	22%	21%	0%	5%	0%	29%	0%	23%

Source: Study strategic dialogues, 2021

Table 16: Portfolios characteristics: rural area community

Portfolio name	Portfolio characteristics			
	Lifecycle capital costs (R/GJ)	Lifecycle fuel and O&M costs (R/GJ)	Drudgery (Hrs/GJ)	Pollutants (kg/GJ)
Energy portfolio 1	1.47	68.03	100.00	100.00
Energy portfolio 2	6.61	81.51	89.57	84.17
Energy portfolio 3	11.77	94.43	75.59	67.91
Energy portfolio 4	26.21	100.00	66.10	51.27
Energy portfolio 5	35.03	78.51	62.77	40.41
Energy portfolio 6	52.36	84.05	56.26	36.20
Energy portfolio 7	61.59	90.48	50.21	31.98
Energy portfolio 8	77.41	69.86	42.04	16.71
Energy portfolio 9	100.00	63.89	35.88	3.72
Energy portfolio 10	61.92	64.60	45.89	5.13

Source: Study strategic dialogues, 2021

During the second round of strategic dialogue sessions, having allowed the panel members to apply their minds to the criteria and alternatives, the panel was presented with an opportunity to use other techniques, the repertory grid (Kelly, 1955) and the plus-minus interesting (De Bono, 1986) techniques, for eliciting criteria in the event they had overlooked important issues. In the process, the panel eliminated all the probable criteria considered non-differentiating. The non-differentiating criteria included the type of food to be cooked, climate, seasonality and family size served were considered non-differentiating criteria.

7.1.3 Alternatives scoring

With the value tree in place (see Figure 30), the panel members were then asked to answer a set of questions to confirm all the low-end objectives (leaves of the tree) that could be interpreted as a performance criterion to evaluate the energy access problem. Then, the panel members selected an attribute for each performance criterion, allowing the measurement of alternatives' performance levels in terms of that criterion. Also, as part of this routine, the scale of each attribute was defined by assigning references to the extreme values.

Under this routine, the panel established how each of the criteria was to be scored through raw data analysis. A distinction was made between global and local scoring. The scoring used for the evaluation is summarised below.

- Investment costs, including appliances (R/GJ) - the alternative cost divided by the highest cost, then multiplied by 100. (global-local scale); and
- Operating costs (R/GJ) - the alternative cost per GJ divided by the highest cost per GJ, then multiplied by 100. (global-local scale).

The sub-criteria under the benefit criterion were selected as:

- Time savings (hours/GJ) - the alternative time savings divided by the highest time savings then multiplied by 100. (global-local scale); and
- Health benefits - Worst 0, Poor 25, 50 Ok; 75 Good and 100 Excellent. (local scale).

The sub-criteria under the fuel type criterion were selected as:

- Availability - Low 0, Medium 50, High 100. (local scale);
- Security of supply - Low 0, Medium 50, High 100. (local scale);
- Pollution (kg/GJ) - the alternative emissions divided by the highest emissions then multiplied by 100. (global-local scale);
- Efficiency - Low 0, Medium 50, High 100. (local scale);
- Environmental impact - Low 0, Medium 50, High 100. (local scale); and

- Alternative use - Worst 0, Poor 25, 50 Ok; 75 Good and 100 Excellent. (local scale).

The sub-criteria under the appliance type criterion were selected as:

- Ease of use - Worst 0, Poor 25, 50 Ok; 75 Good and 100 Excellent. (local scale);
- Safety - Worst 0, Poor 25, 50 Ok; 75 Good and 100 Excellent. (local scale).; and
- Cultural fit - Worst 0, Poor 25, 50 Ok; 75 Good and 100 Excellent. (local scale).

A mixture of global and local scales was used for costs, time savings, pollutants and efficiency. Given that the process was iterative, the scoring was changed as the researcher went through the process with the panel members. All the quantitative scales used in the model were linear, i.e., the scales used assume that the decision-maker's preferences increased linearly. The justification for the use of linear scales was that linear scales are very good for measurements in the real world. For local scales, the panel of experts agreed on the use of a five-point scale and the meaning of the terms Worst, Poor, OK, Good and Excellent with Excellent being the most positive rating and Worst being the most negative rating on the five-point scale.

7.1.4 Determining attribute weights and partial value functions

The computation of the overall scores required the assignment of weights on all parent criteria. As discussed in Chapter 3, weights represent the relative importance of each sub-criterion relative to the other sub-criteria of the parent criteria. In other words, the weights represent the intrinsic value a decision-maker places on each child criteria. The swing weights approach (Goodwin and Wright, 2001) was used in this investigation, as stated in Section 3.2. For numerous reasons, the swinging method was deemed the most appropriate strategy. The technique was chosen for two reasons: first, it is simple to use, and second, it does not require knowledge of the structure of marginal value functions. When utilized in a hierarchical form, the swing weight elicitation technique has also been demonstrated to reduce the occurrence of equalizing bias (Montibeller and Von Winterfeldt, 2015). In comparison to the smart variety, the swing elicitation has also been reported to provide more stable weights (Lienert et al., 2016).

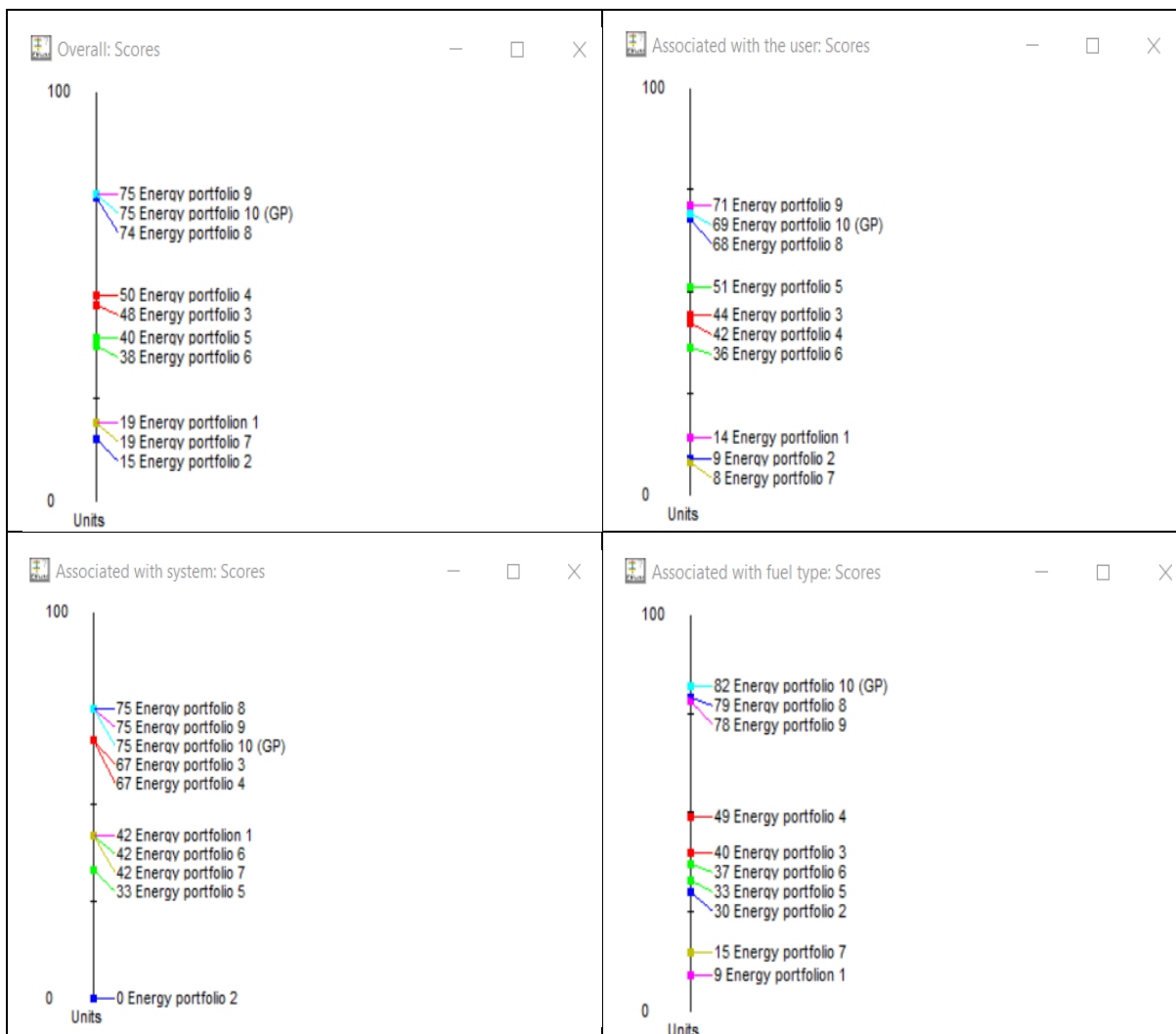
Once the attribute had been identified and finalised, the panel was then requested to assign weights for each parent criterion on a scale from 0 to 100, with one representing no importance and 100 high importance. The following question was posed to the panel of experts "*On a scale from 0 to 100, with one representing no importance and 100 high importance, which criteria do you consider to be important?*" The user criterion was considered to be the most important, followed by the fuel type criterion. Appliance/system criteria were adjudicated to be

of least significant. This process was based on the problem structuring framework developed in Chapter 5. This process was necessary for recognizing conflicting interests. The rating process involved implicit judgments. Again, the process was iterative, meaning that weights were changed as the researcher went through the process with the panel members.

7.2 Evaluation results

Analysis of the V.I.S.A groupware scores thermometer revealed that, overall, portfolio nine and portfolio ten were the most preferred with overall scores of 75. Portfolio nine comprised bioethanol fuel, LPG and a micro-grid made up of CCGT, solar PV, solar with storage and wind. The tenth portfolio (the GP portfolio) was made up of bioethanol fuel, LPG, and a micro-grid made up of CCGT, solar PV and wind.

Figure 31: V.I.S.A groupware scores for the rural area scenario



Source: MAVT model, study strategic dialogues

The eighth strategy, portfolio eight, comprised of firewood, bioethanol fuel, LPG and a micro-grid made up of CCGT, OCGT, solar PV, solar with storage and wind ranked third, with an overall score of 74. Portfolio two, which comprised mostly rudimentary fuels (firewood and kerosene) was rated as the worst strategy with an overall score of 15. Figure 31 presents a summary of the overall score and the associated overall scores for the three-parent criteria.

Before comparing the results achieved using the GP technique and those acquired using the MAVT technique, it is necessary to explain how the various problems were solved using the various methodologies. To begin, the GP approach converts continuous optimization into a set of solutions (discrete set). This allows for a comparison with the discrete solutions generated by the MAVT technique. The methodology established allows for the transition from continuous to discrete optimization.

The results obtained from the MAVT application confirm those obtained from the technical evaluation (GP portfolio). The augmented Chebychev GP portfolio comprised of bioethanol fuel (22%), LPG (21%), CCGT (5%) solar PV (29%) and wind (23%). As shown in Figure 31, the GP portfolio also ranked high, the same level as the MAVT portfolio. Table 17 presents a summary of the resulting energy portfolios under the two different evaluation procedures.

Table 17: Energy portfolios under two different evaluation procedures

Energy source	MAVT Portfolio	GP portfolio
Bioethanol fuel	5%	22%
LPG	20%	21%
CCGT	5%	5%
Solar PV	30%	29%
Solar with Storage	15%	0%
Wind	25%	23%

Source: Augmented Chebychev GP and MAVT models

These results confirmed that, even with the inclusion of qualitative criteria, there is no place in the energy mix for low-income households for rudimentary fuels such as firewood, kerosene and technologies such as electrification through the grid electricity and diesel generation. As observed under the GP evaluation, the high lifecycle costs and high levels of pollution

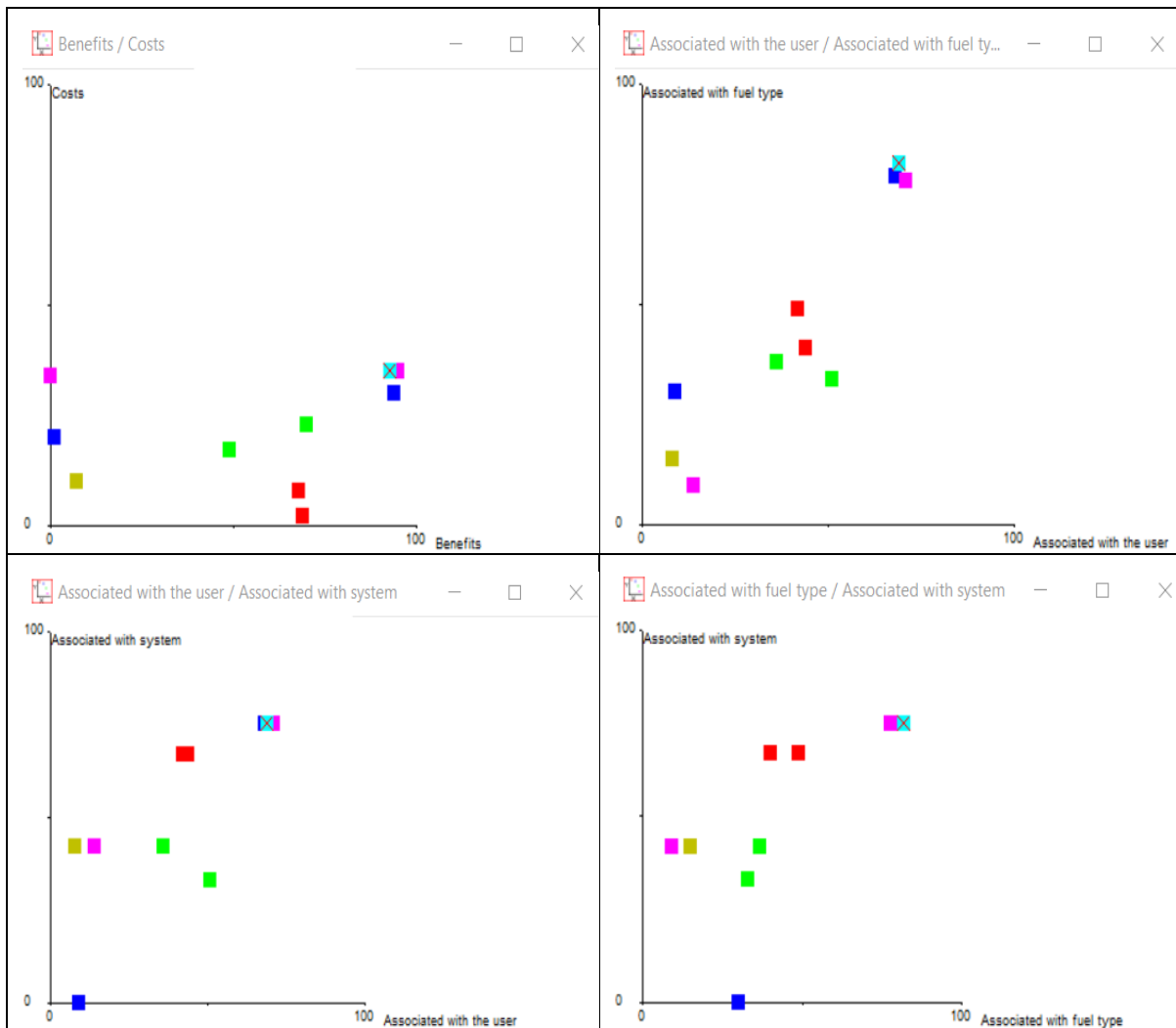
associated with kerosene and diesel made these technologies very uncompetitive from a benefit-cost perspective and overall, after accounting for all the other criteria considered under the MAVT framework. The poor performance of CCGT in both the high ranked GP and the MAVT portfolios relative to solar PV, wind, bioethanol and wind technologies were also explained by the high overall life cycle costs and availability in isolated rural villages.

Despite the inclusion of cultural acceptability as one of the criteria, firewood was excluded from the best-ranked portfolio. With a 5 per cent firewood component in its energy mix, the eighth portfolio ranked equally high with an overall score of 74 (See Figure 31). The study, therefore, cautions that while firewood performed poorly in the initial scenario and the overall energy mix, firewood will continue to be relied upon among the poorest, as posited in academic and empirical investigations (Davis, 1998; Goldemberg, 2000; Thom, 2000; Gaunt, 2005; and Madubansi and Shackleton, 2006; Matsika et al., 2013, Shackleton, 2017). This finding implied that further portfolios in which input parameters and assumptions were varied were needed to validate the results. Therefore, sensitivity and scenario analysis were conducted as part of the results validation procedure.

Following the framework developed for the study (see Chapter 5) and as discussed above, the panel of experts determined that the final decision could not be taken based on the results of the overall scores. This determination was because the overall score only indicated the scale of an alternative and not its relative efficiency, as ratings did not provide performance information. As a result, X-Y plots for all parent criteria were produced to assess the trade-offs among criteria. All dominated alternatives were also identified in the process. Figure 32 presents a summary of the results of the X-Y plots for the cost-benefit and the three-parent criteria.

The X-Y plots revealed that wind, solar PV, and bioethanol portfolios seemed to be the best alternatives to select. These are portfolio nine, portfolio ten and portfolio eight. This again confirms the dominance of LPG, solar PV, bioethanol and wind as the most preferred energy choices among low-income households in South Africa.

Figure 32: X-Y plot results



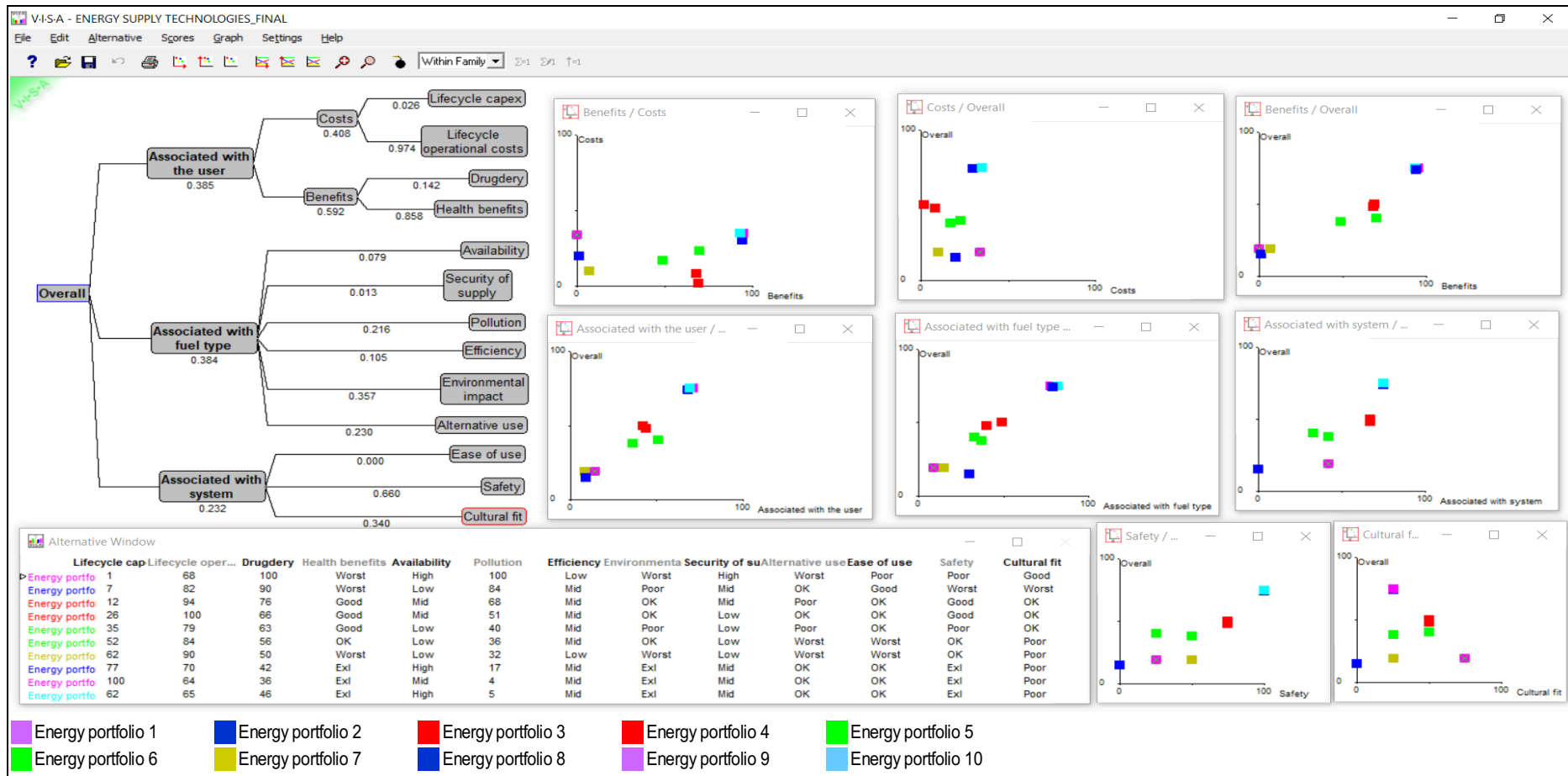
Source: V.I.S.A groupware model, study strategic dialogues

- Energy portfolio 1
- Energy portfolio 2
- Energy portfolio 3
- Energy portfolio 4
- Energy portfolio 5
- Energy portfolio 6
- Energy portfolio 7
- Energy portfolio 8
- Energy portfolio 9
- Energy portfolio 10

7.2.1 Sensitivity Analysis

A thermometer indicates scenario scores in VISA groupware's sensitivity analysis module. The thermometer is used to categorise and understand results. A thermometer chart depicts the ranking and 'distance' between the alternatives in a clear visual manner. The panel was unsure about the robustness of the options to changes in weights and the accuracy of the weighting system after determining that portfolios comprising bioethanol fuel, LPG wind, solar PV, and bioethanol seemed to be the best alternatives to select using the overall scores thermometer and the X-Y plots. As a result, a sensitivity analysis was carried out to determine the level of uncertainty and the impact of different weights.. Figure 33 presents the Sensitivity Analysis results.

Figure 33: Sensitivity analysis results for the rural community scenario



Source: V.I.S.A groupware model; study strategic dialogue sessions

Figure 33 shows that the portfolio for the efficient frontier for the set of weights would comprise a portfolio made up of bioethanol fuel, LPG, CCGT, solar and wind, portfolio nine. Portfolio nine would most likely be preferred to a portfolio made up of mostly firewood, kerosene and grid-based electricity. As discussed earlier, portfolio eight, which is made up of 5% firewood, appears to still perform better when the weights assigned on costs are changed. This result is explained by the low upfront costs associated with the technology. This preference was because small changes in costs result in even more significant benefits. Given this new set of weights, the panel's preference for a portfolio made of wind and bioethanol seems reasonable with the new set of weights. The results show that portfolios eight, nine and ten had the highest benefit-cost ratios.

The results of the Sensitivity Analysis show that, in terms of relative efficiency, portfolios eight, nine and ten would still have the highest overall score and remain the most preferred option when weights on technology and safety were varied. Portfolios one and two would again perform worst on the overall rating and remain the least attractive options in terms of relative efficiency if the benefits, user, technology and safety criteria weights were varied. Once again, this result could best be explained by portfolio two's poor performance, which was largely made up of kerosene and firewood as observed under the GP model and the MAVT scenario for rural areas.

If the system criteria weights were varied, portfolio nine would remain the most attractive alternative policy choice in terms of relative efficiency with the highest overall score. When cultural fit criteria weights were varied, portfolio nine would still have the highest overall score making it the most preferred option. Portfolio two would again perform worst and remain the least attractive option in terms of the relative efficiency if the cultural criteria weight was varied.

7.2.2 Scenario Analysis

Informal urban settlements

In the previous chapter, the researcher ran the GP model for two different community types with different resource availability conditions, namely a "typical rural" case and an "informal urban" case. Thus far, the MAVT technique has only been applied to the rural case scenario. It is worthwhile reiterating that energy consumption patterns in these two different settings mirror each other, as observed by Nabudere in 2006 (Nabudere, 2006). Energy resource availability in these two settlements, however, differs substantially. As a result, the panel of experts found it worthwhile to apply the same MAVT model to an informal urban informal settlement to assess the impact of deploying the different energy supply alternatives. The

same definition used in Chapter 6 was used to define the term informal urban area. These are illegal settlements with no access to energy, water, sanitation and decent accommodation.

The scenario was also elicited as part of the second round of the strategic dialogues, which were conducted with the panel of experts. The panel of experts was asked the following extended question “Do you still stand with your agreed position on the notion that energy consumption patterns in informal settlements mirror those in rural areas and policies aimed at reducing energy and poverty, in general, should not discriminate communities living in informal urban settlements?”. What other settlement types can be considered in addition to the informal urban area settlement?” Feedback was collected, collated and reviewed iteratively with the panel of experts. Resultantly, the experts agreed on pursuing the informal urban settlement scenario only.

The same ten energy supply strategies evaluated under the rural area scenario were evaluated in this routine. Table 18 and Table 19 provides summaries and technology characteristics of the ten energy supply portfolios considered for the informal urban area scenario. These same characteristics were used under the augmented Chebychev GP model.

Table 18: Energy supply portfolios: informal urban area

Portfolio name	Portfolio components (mix)									
	Firewood	Kerosene	Bioethanol fuel	LPG	Grid electricity	CCGT	OCGT	Solar PV	Solar with storage	Wind
Energy portfolio 1	45%	50%	0%	5%	0%	0%	0%	0%	0%	0%
Energy portfolio 2	35%	45%	5%	15%	0%	0%	0%	0%	0%	0%
Energy portfolio 3	30%	40%	15%	10%	0%	0%	0%	5%	0%	0%
Energy portfolio 4	25%	35%	10%	20%	0%	0%	0%	10%	0%	0%
Energy portfolio 5	20%	10%	20%	25%	0%	0%	0%	15%	5%	0%
Energy portfolio 6	15%	5%	25%	25%	0%	0%	0%	20%	10%	0%
Energy portfolio 7	10%	5%	20%	25%	0%	0%	0%	25%	15%	0%
Energy portfolio 8	5%	0%	25%	25%	0%	0%	0%	25%	20%	0%
Energy portfolio 9	0%	0%	20%	25%	0%	0%	0%	30%	25%	0%
Energy portfolio 10	21%	2%	23%	20%	0%	0%	0%	34%	0%	0%

Source: Study strategic dialogues, 2021

Table 19: Portfolios characteristics: informal urban area

<i>Portfolio name</i>	<i>Portfolio characteristics</i>			
	<i>Lifecycle capital costs (R/GJ)</i>	<i>Lifecycle fuel and O&M costs (R/GJ)</i>	<i>Drudgery (Hrs/GJ)</i>	<i>Pollutants (kg/GJ)</i>
<i>Energy portfolio 1</i>	2.35	102.88	100.00	100.00
<i>Energy portfolio 2</i>	4.07	102.75	102.19	80.64
<i>Energy portfolio 3</i>	9.07	102.15	92.35	70.44
<i>Energy portfolio 4</i>	16.51	100.00	92.55	59.92
<i>Energy portfolio 5</i>	34.98	89.68	70.56	46.41
<i>Energy portfolio 6</i>	52.76	93.41	64.41	36.18
<i>Energy portfolio 7</i>	70.42	92.81	58.70	25.93
<i>Energy portfolio 8</i>	82.34	92.56	52.21	15.62
<i>Energy portfolio 9</i>	100.00	91.95	46.50	5.37
<i>Energy portfolio 10</i>	44.18	89.88	57.92	46.42

Source: Study strategic dialogues, 2021

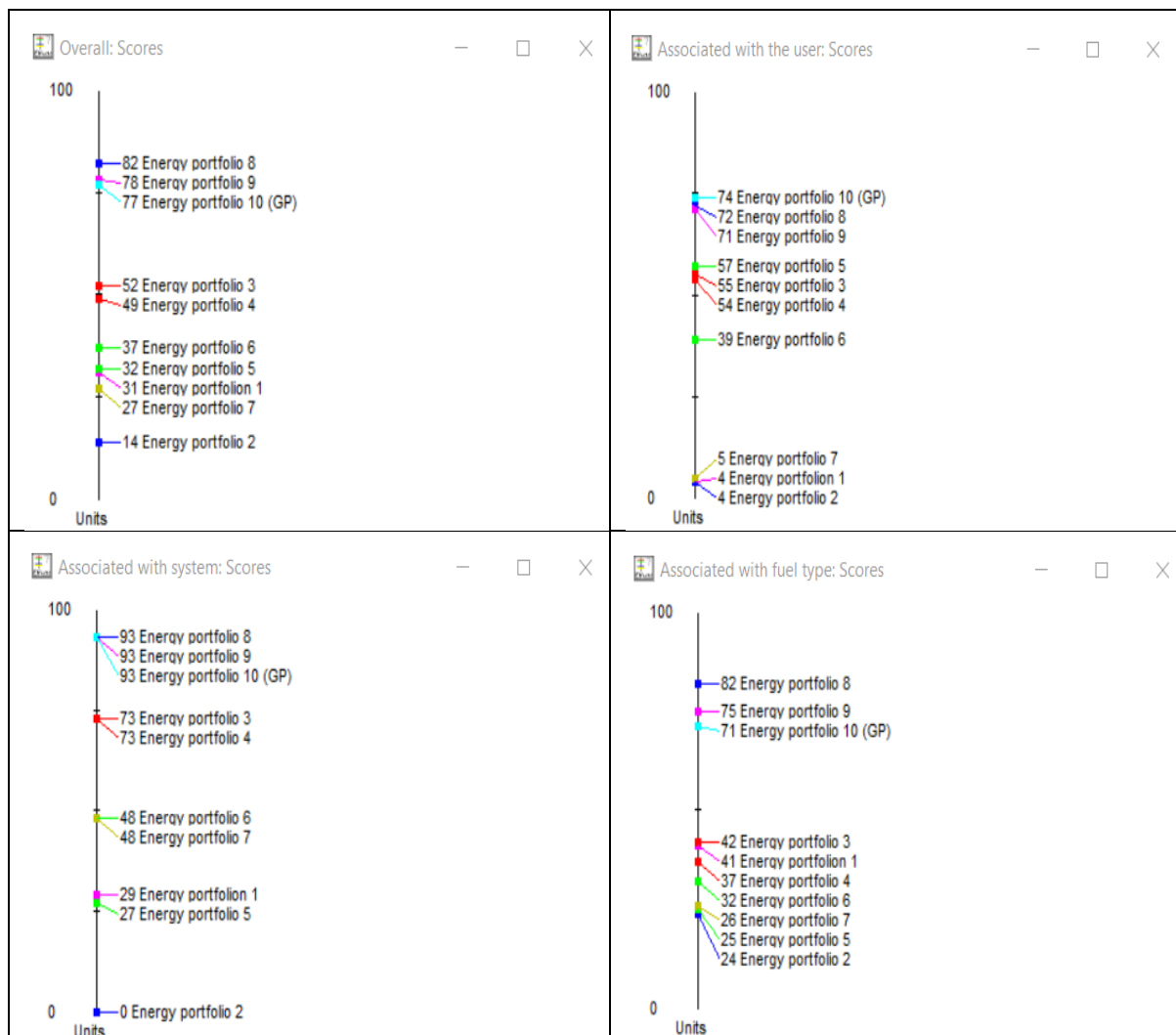
The same procedures applied for the rural scenario were also followed under the informal urban scenario.

7.2.3 MAVT model results for the informal urban area scenario

Similar to the findings in the rural areas scenarios, the MAVT scores for the informal urban informal settlement thermometer revealed that portfolio eight, which included firewood, bioethanol fuel, LPG, solar PV, and solar with storage, was deemed the best option with an overall score of 82. With a total score of 78, Portfolio nine was the second-best approach, consisting of bioethanol fuel, LPG, solar PV, and solar with storage. Portfolio nine differed from portfolio eight in that it did not include firewood.

Portfolio ten (the informal urban area GP portfolio, see also Figure 27) which comprised firewood, kerosene, bioethanol fuel, LPG and solar PV, ranked third, with an overall score of 77. Portfolio two, which comprised mostly rudimentary fuels (firewood and kerosene,) was rated as the worst strategy with an overall score of 14. The results obtained from the MAVT application confirm those obtained from the technical evaluation (the GP model) and those obtained from the MAVT application for a rural area community. Figure 34 presents a summary of the overall score, together with the associated overall score for the three-parent criteria.

Figure 34: V.I.S.A groupware scores for the informal urban scenario



Source: MAVT model, study strategic dialogues

According to the results of the analysis of the informal urban area scenario, as observed under the GP model and the MAVT model for a rural community, owing to the limitation on extending the grid to informal urban settlements, solar PV was found to be the only feasible option for supplying micro-grid to power electrical appliances for low-income households living in these areas.

Again, the results confirm the energy ladder postulate. Portfolio eight, which was the best-ranked portfolio, was made up of 21 per cent firewood. This result implied that firewood would continue to play a role in the energy mix of low-income communities residing in informal settlements. The study results also confirmed empirical arguments on the role of firewood in low-income households (Cherni et al., 2007). This argument was buttressed by the evidence

of increased use of firewood in Zimbabwe due to shrinking incomes discussed earlier (Dube et al., 2020; Thomson Reuters Foundation, 2021).

The problem of continuous firewood use can be alleviated by incorporating bioethanol fuel into the mix through government-sponsored initiatives, similar to those made previously under the GP model and the MAVT application for rural areas. This can be supplemented by sustainable firewood extraction and use in informal urban settings.

In terms of policy implications, the study makes the case that, based on the research findings, poverty reduction efforts for the poor in rural areas should not be limited to these areas alone but should also include low-income families living in informal urban settlements. The MAVT model established for the study proved to be effective in various situations. Table 19 compares the resulting energy portfolios (Appendix C) for isolated rural regions and informal urban areas scenarios, as well as those derived using the GP process for informal urban areas, side by side.

Table 20: Energy portfolios under two different scenarios and evaluation procedures

Attribute	MAVT Portfolio [Rural area]	MAVT Portfolio [Informal urban area]	GP portfolio [Informal urban area]
Firewood	0%	5%	20%
Kerosene	0%	0%	2%
Bioethanol fuel	5%	25%	23%
LPG	20%	25%	19%
CCGT	5%	0%	0%
Solar PV	30%	25%	34%
Solar with Storage	15%	20%	0%
Wind	25%	0%	0%

Source: Augmented Chebychev GP model, MAVT model

The high quantities of firewood and kerosene in the technical scenario for rural areas are notable disparities between the MAVT results and the GP scenario for informal urban areas. These discrepancies can be explained by the MAVT models' incorporation of non-qualitative

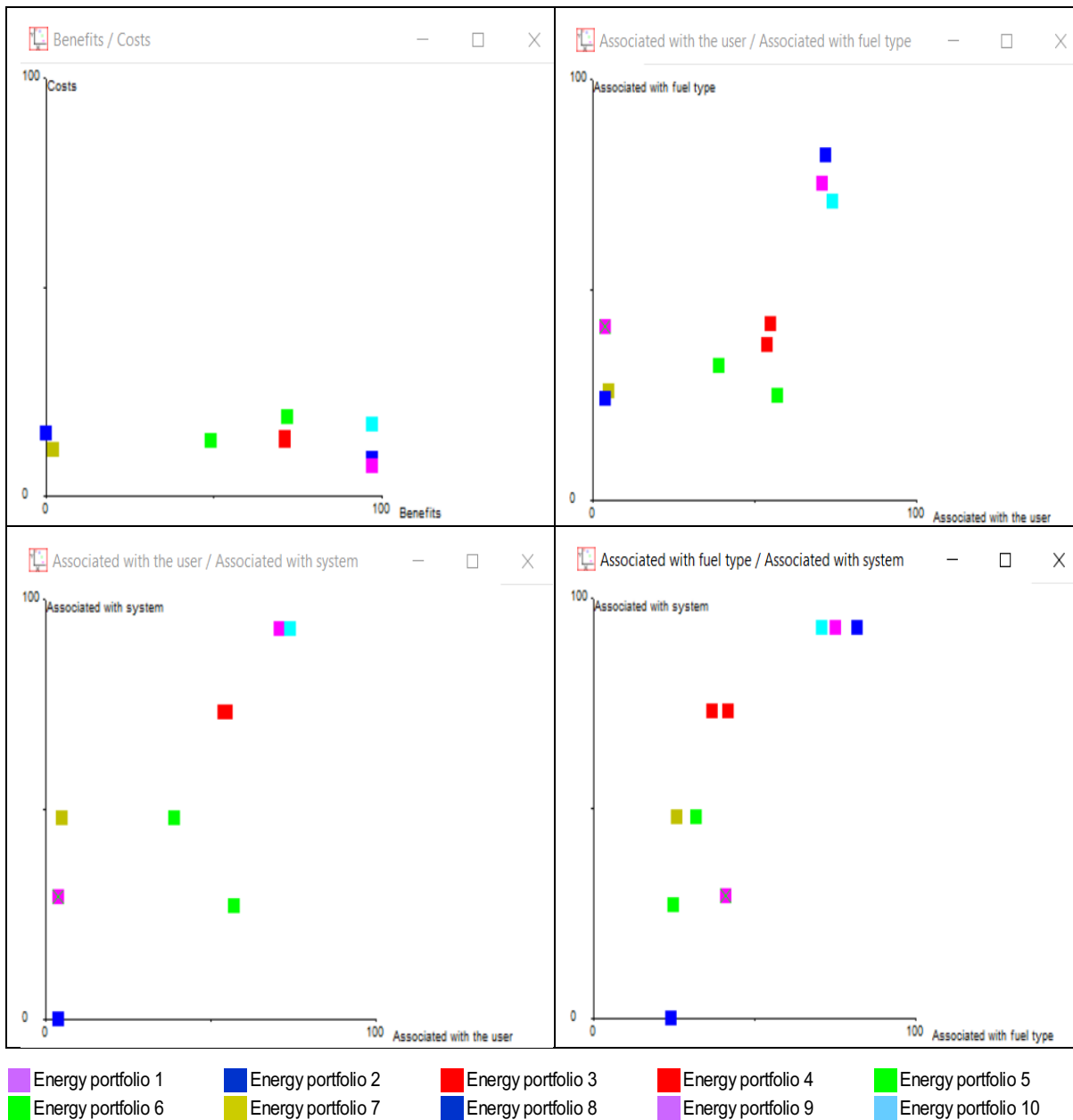
elements such as safety and cultural considerations. Given the ever-increasing informal urban area populations and the expansion of informal settlements in South Africa, decision-makers should consider quantitative and qualitative factors when planning energy solutions. People migrating from rural areas to informal urban areas and people who continue to follow traditional norms make up these communities.

Regardless of the differences between MAVT results and the GP scenario for informal urban areas, what was clear from the study results was that there is no place in the energy mix for low-income households for rudimentary fuels such as kerosene and electrification through the central grid. It was also worthwhile noting that despite the results of both the MAVT and GP models indicating that there is no place for firewood, firewood will nonetheless continue to be relied upon among the poorest, as posited in empirical investigations (Davis, 1998; Goldemberg, 2000; Thom, 2000; Gaunt, 2005; and Madubansi and Shackleton, 2006; Matsika et al., 2013, Shackleton, 2017).

X-Y plot results for the informal urban area community scenario

Following the framework developed for the study and as discussed earlier, the panel also decided that the final decision for the informal urban areas scenario could not be taken based on the results of the overall scores shown in Figure 34. X-Y plots for all parent criteria were produced to assess the trade-offs among criteria. All dominated alternatives were also identified in the process. Figure 35 presents a summary of the results of the X-Y plots for the cost-benefit and the three-parent criteria.

Figure 35: X-Y plot results for the informal urban area community scenario



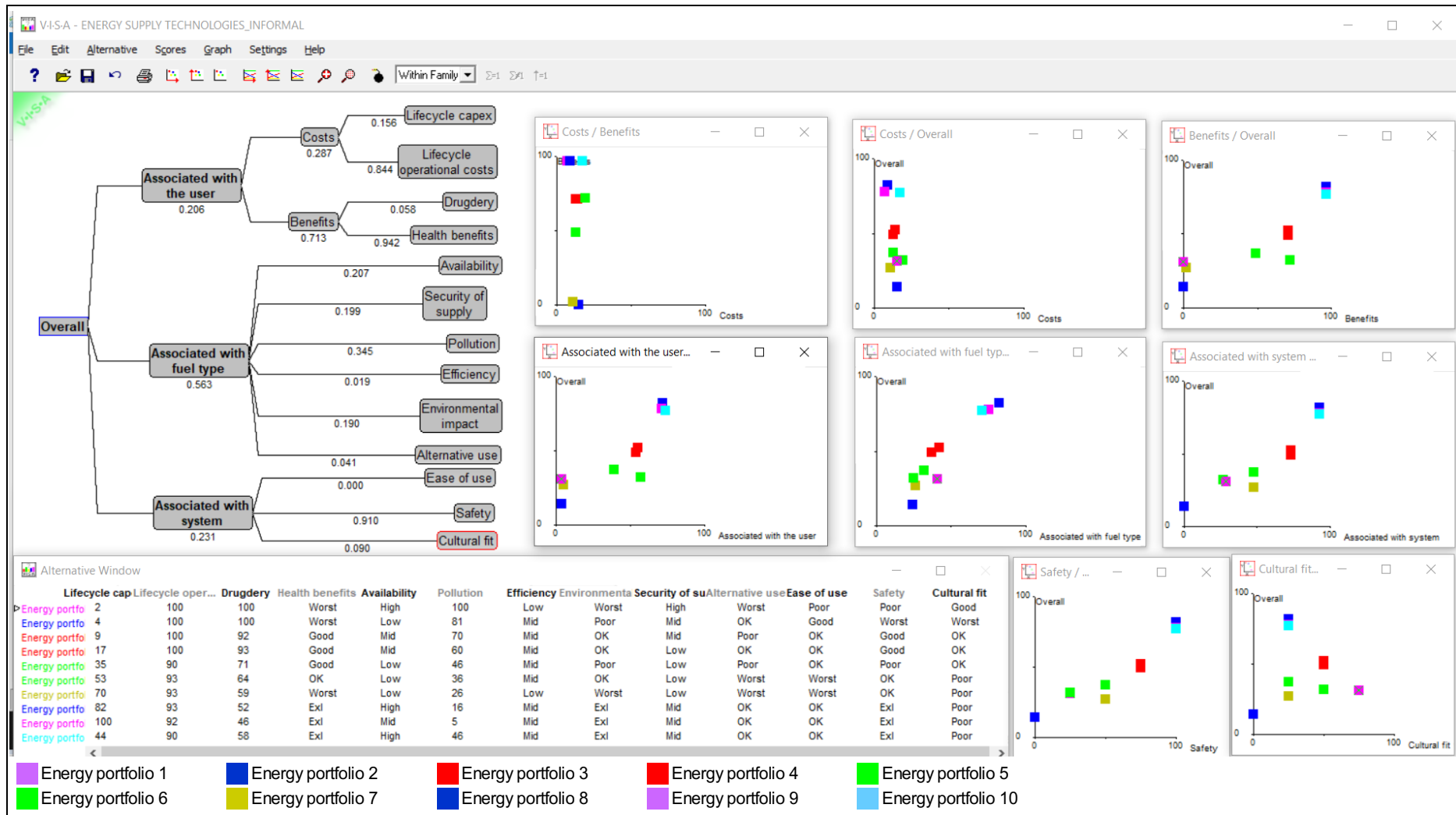
Source: MAVT model, study strategic dialogues

Similar to results obtained under the rural areas scenario, the X-Y plots revealed that portfolios comprised of bioethanol fuel, LPG, solar PV seemed to be the best alternatives to select.

7.2.4 Sensitivity Analysis

Similarly, following the framework developed for the study in Chapter 5, Sensitivity Analysis was also performed to ascertain uncertainty and the impact of varying weights. Figure 36 the Sensitivity Analysis results for a typical informal urban settlement community in South Africa.

Figure 36: Sensitivity analysis results: informal urban area



Source: V.I.S.A groupware model; study strategic dialogues

Figure 36 shows that, under the informal urban settlement scenario, the portfolio for the efficient frontier for the set of weights would comprise a portfolio made up of firewood, bioethanol fuel, LPG, solar PV and solar with storage. This portfolio option (portfolio eight) would be the most preferred relative to portfolios made up of solely firewood, kerosene, bioethanol fuel and LPG. As observed under the rural area scenario, portfolio eight, portfolio nine and portfolio ten for informal urban areas appeared to perform better when the weights assigned on user preferences were changed. This result was also explained by the low upfront costs associated with the firewood in portfolio ten. This preference was because small changes in costs result in even more significant benefits.

The sensitivity analysis results for the informal urban scenario showed that, in terms of relative efficiency, except for user and system criteria, portfolio eight would still have the highest overall score and remained the most preferred option when weights on technology and safety were varied. Portfolio two would again perform worst on the overall rating and remain the least attractive option in terms of relative efficiency if the benefits, technology and safety criteria weights were varied.

Varying the system criteria weights made the tenth portfolio (the GP portfolio for informal urban areas) an equally attractive alternative policy choice relative to portfolio eight in terms of relative efficiency with the highest overall score. When cultural fit criteria weights varied, portfolios eight, nine, and ten would still have the highest overall score, making it the most preferred option. Portfolio two would again perform worst and remain the least attractive option in terms of the relative efficiency of the cultural criteria weight were varied. These informal urban area results are consistent with results obtained under the augmented Chebychev model and the MAVT scenario for rural areas.

7.2.5 Adopting the MCDA framework to tackle the complexities of real-life policy analysis and outcomes

The scientific contributions of the present study go beyond the MCDA framework developed for the study as it tackles both the quantitative and qualitative policy impact of assessing intervention strategies aimed at increasing energy access among the poor. As discussed in Chapter 6, the author's work in developing the MAVT model and applying it to theoretical energy access problems has clear implications for practice..

Results obtained from the study support the continuing emphasis on the suitability of the GP and MAVT techniques for optimising objectives relating to competing activities in energy planning. Under the framework developed, the GP technique handles quantitative variables,

and its results can only be analysed from a quantitative perspective. Yet, in real-life situations, qualitative criteria also ought to be considered to improve the quality of decisions. The MAVT framework, which was essentially an extension of the augmented Chebychev GP model introduced in Chapter 6, made the modelling robust by incorporating quantitative and qualitative criteria.

Decision-makers in the public policy-making environment officials confronted with large-scale problems can make use of the MCDA framework developed in this study. As discussed in Chapter 3 (Section 3.3.2 and Section 3.3.5), this is because the GP and the MAVT models developed for the study was designed to handle problems with a limited and discrete set of alternatives, which can be appraised based on contradictory objectives (Belton and Stewart, 2002). While the MAVT technique has been widely applied to decision-making in different sectors (Munda, 2005), the author is not aware of any literature where the question of seeking the optimal energy mix for poor households. This is another novelty of the present study. The extension of the augmented Chebychev GP technique to the MAVT technique to address an energy access problem among the poor in South Africa.

7.2.6 Implications for policy implementation and research

Analysis of the results based on the Chebychev GP and the MAVT models showed that while it is cost-optimal to pursue electrification in conjunction with other short-term augmentation solutions to meet South Africa's universal electrification targets, sustainable energy access rates among low-income households located in isolated rural areas can be achieved by increasing the share of clean energy generation technologies in the energy mix. The study challenges the South African government's unbalanced emphasis on grid-based electrification as the means to increase energy access. Instead, it calls for a portfolio-based intervention. It posits that the focus should be on off-grid, micro-grid electrification underpinned by solar, wind and gas combined with either LPG or bioethanol, depending on the conditions. Similar conclusions have been reached elsewhere (Bueno-López et al., 2019).

Results obtained from the sensitivity analysis conducted indicates that, regardless of changes to input parameters to the augmented Chebychev GP and MAVT models, renewable energy sources, in particular bioethanol and solar, can play a major role in increasing access to affordable energy services in South Africa. This finding is buttressed by the United Nations Development Programme (UNDP) which found that renewable energy sources are *“highly responsive to overall energy policy guidelines and environmental, social and economic goals”* (UNDP et al., 2000). Given this limited experience with the optimal solution discussed above,

the following section examines mechanisms for making policy choices and implementing the chosen strategies.

Given the attractiveness of renewable energy sources and the lead times between planning, investing, and deployment, the study results imply a complete shift from the current focus on mega-projects and the grid-based rural electrification programme. The shift implies the following seven policy reconfigurations:

1. First, as shown by a preference for energy supply portfolios with a high share of renewable energy, it is essential to **increase the share of affordable energy services**. A shift from the loop-sided focus on grid-based rural electrification as the holy grail for increasing access to affordable energy among the poor. Renewable energy sources have proven to be cheaper than conventional grid-based electricity. Prices of many renewable energy technologies are expected to continue on a downward trajectory. This is expected to make renewable energy more attractive than the conventional grid as a least-cost option.
2. Second, the results of the GP and MAVT applications indicated a preference for micro-grid-based interventions. The study, therefore, suggests **improving energy governance** through the replacement of the government as a major investor in energy generation infrastructure. Participation of the private sector in micro-grids, anchored on renewable energy sources as has been observed in the past decade, will go a long way in improving energy governance. The private sector has proven to be more efficient in deploying resources than the government. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has successfully channelled considerable private sector investment and expertise in the renewable energy industry in South Africa (Eberhard et al., 2014).
3. Third, based on the study framework results, preference should be given to portfolios with high employment creation capacity. Thus, the study suggests a shift to policies aimed at **stimulating economic development** through investments in projects that have an immediate impact with high job creation potential. Therefore, emphasis should be placed on the economic value of time and interventions that result in improved employment outcomes for low-income communities. Renewable energy technologies are quick to deploy, modular and have a higher job creation potential, construction and lifetime jobs. Private sector participation in public infrastructure will also go a long way in reducing the burden on the fiscus. This policy alteration should allow the government

to deploy the scarce fiscal resources to other needy and neglected interventions such as social protection, housing, water and sanitation and education.

4. Fourth, the study results showed environmental protection to be of significant importance. As such, the study recommends the **management of energy-related environmental impacts** by emphasising on environmental protection on government energy policy in line with the country's international obligations on reducing carbon emissions. Third, based on the study framework results, preference should be given to portfolios with high employment creation capacity. Thus, the study suggests a shift to policies aimed at stimulating economic development through investments in projects that have an immediate impact with high job creation potential. Therefore, emphasis should be placed on the economic value of time and interventions that result in improved employment outcomes for low-income communities.
5. Fifth, portfolio-based interventions have shown to be the optimal way to ensure energy access among the poor. Many renewable energy technologies are particularly suited to micro-off-grid applications. These technologies could improve the flexibility of the grid by distributing generation across the country, closer to loads of any magnitude. Solar PV systems and mobile bioethanol infrastructure can be easily deployed even in informal areas where Eskom is prohibited by law from extending its grid. Policies thus need to be reconfigured to **ensure the security of supply through diversity** by emphasizing energy security and diversification.
6. Sixth, the study has shown that firewood's continued use, especially in informal urban areas, is set to continue unabated. As such **sustainable firewood collection and use; and deforestation regulations should be enforced** to curb the uncontrolled cutting down of trees for firewood, particularly near urban areas. This is also expected to enable the required shift to cleaner fuels.
7. Seventh, the study results have shown a preference for clean fuels in line with the energy ladder postulate. **Therefore, interventions are needed to support research** and the introduction of clean fuels in developing countries among low-income communities to accelerate the transition to clean household energy

Planners seized with formulating and implementing government policy in South Africa are encouraged to reconfigure the current energy grant and subsidies regime in favour of interventions that result in immediate impact. For instance, instead of spending billions of rand on subsidised paraffin for indigent households, the same resources can be utilised to deploy bioethanol distribution infrastructure. Bioethanol fuel is cleaner and can be produced locally implying local employment creation and import substitution. Adding solar PV to the mix will

help cater to these indigent families' electricity needs. A question that arises is, "when implementing the recommended strategies discussed, how can the policy decisions be promoted and defended in practice?" The following section addresses this question.

7.2.7 Strategies for promoting and defending policy decisions

In practice, policy development and adoption in the public sector is often characterised by opposition to proposals which often culminates in demonstrations by opponents of the decision. The interests of stakeholders and stakeholder groups in a decision are not always aligned. They usually do not share the same views about problems and the proposed solutions. This diversity of views makes policy-making challenging. Decision-makers have to account for these divergent views, and goals and they will need to reconcile different perspectives to avoid the perception that the resulting policies are imposed on other groups. The views and goals of decision-makers and those of beneficiaries, therefore, need to be aligned to ensure seamless placement of proposals on the policy agenda and for democratic adoption. The study puts forward several strategies for defending the decisions to the citizens, press and political principals. These strategies include:

- **Ensuring stakeholder involvement through the decision-making stages.** As discussed in Chapter 3, it is essential to involve stakeholders using top-down and bottom-up techniques (refer to Section 7.1 and Figure 12). There is broad agreement in MCDA literature that the involvement of stakeholders in policy development cultivates a sense of joint ownership over policies and hence helps build consensus the need and the relevance of interventions. The engagement of stakeholders should be viewed as a continuous and iterative process that covers the entire spectrum (initiation, development and implementation) of the decision-making process. The study advances a thesis that consensus is a prerequisite for the successful initiation, development and implementation of strategies in the public sector. There are several reasons which support the notion.
 - First, consensual policy-making is characterised by iterative processes of proposals and feedback, which allow legitimate concerns to be taken into account and reduce the likelihood of strong opposition by some stakeholder groups.
 - Second, consensual policy-making forces different stakeholders to work together collectively rather than in unproductive opposition. For example, Lindell (2004) observed that in Sweden, *"even though the stakeholders are opponents in appearance, the everyday work in parliamentary commissions and joint working*

groups is done by a small group of professional elites whose agenda is not always optimised for their members only, but the interest of the nation.”

- **Ensuring an iterative process taking all factors into account.** Academic literature on policy development and implementation shows broad support for iterative policy development (see also Belton and Stewart, 2002); Eden and Ackermann, 2006; Rosenhead and Mingers, 2004). An iterative process facilitates the early identification of potential opponents to the proposals and addresses part of their concerns through adjustments in subsequent iterations of the policy proposals. The study proposes a policy development and implementation underpinned by a process of negotiation, compromise and conflict resolution to ensure acceptable policy decisions and technical solutions (see Figure 12).
- **Formulating clear objectives of the proposed intervention.** Aligned to the need for stakeholder involvement, the study recommends communication of the objectives of the proposed intervention. Policies are more likely to succeed if their intentions are focused and well defined rather than ambiguous. Evidence suggests that interventions are more likely to be adopted and implemented if the pressure to reform comes from the beneficiaries of the intervention. Clear communication on the objectives of proposed interventions and how these goals can be reached is one way to secure stakeholder support for new policy interventions. It is also necessary to avoid strategies advocated mainly by powerful minority groups.
- **Conducting policy experimentation and pilots.** Policy experimentation and the recourse to pilot schemes can prove powerful in testing out policy proposals and, by virtue of their temporary nature and limited scope, overcoming fears and resistances by specific groups of stakeholders. In South Africa, given the devolved powers, policy experimentation can be facilitated by the national departments in selected provinces. Only with evidence of success can strategies be rolled out across provinces.

The study has demonstrated that focusing on building consensus on the strategic direction for intervention enhances stakeholders' understanding of synergies, trade-offs, and constraints and improves the likelihood of their support for policies emerging from the jointly agreed strategies.

7.3 Chapter conclusion

This chapter presented an MCDA procedure that can support energy planning decision-making processes for energy access among poor communities living in remote rural areas

identified by Hughes et al. (2017) and discussed in Section 2.2. The applied approach, a combination of the linear programming paradigm based on the GP technique and the MAVT technique, proved to be a useful technique that can aid public sector energy planning and decision-making.

The study demonstrates the benefits of applying the framework developed to a classical problem encountered in the public sector, a dynamic multi-technology decision problem under uncertainty involving several conflicting objectives. In addition to investment and operational cost considerations, the study observed that thermal efficiency is becoming more and more critical in energy planning together with sustainability, environmental, social and political considerations.

As demonstrated in this chapter, the developed framework was useful for the assessment of different energy sources for poor communities. It was also valuable for evaluating the impact of changing key parameters to develop different scenarios. It is expected that technological changes in the energy industry will profoundly affect the study's recommended energy portfolio and future energy mixes for the country and low-income communities locally and globally. The next chapter presents the research findings, conclusions and recommendations.

CHAPTER 8

RESEARCH FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

8.0 Chapter introduction

This chapter synthesises the salient findings from the previous chapters to provide recommendations for developing and implementing energy access policies and interventions among the poor in South Africa. The study was based on exploring the possibility of developing, applying and validating a multi-objective and consensus-driven framework. The framework is a decision aid designed to assist decision-makers with structuring energy planning problems among low-income households and aid strategic decision-making processes in the public sector. In attempting to cover energy planning problems, five research objectives were formulated in Chapter 1.

This chapter examines the importance of the study and how the findings of the study may be adopted for policy, practice, theory and future research studies. The chapter looks at conclusions drawn from the study results and explains the importance of these findings for practice, theory or policy.

The chapter concludes with recommendations and suggestions for areas that need further research in supporting public sector strategic decision-making processes in energy and development planning. The section on recommendations outlines particular measures that should be performed in terms of legislation, practice, theory, and future study.

8.1 Research findings

8.1.1 Status quo: energy supply among low-income households

The study found that the main challenge facing low-income families in rural South Africa was access to modern, clean, and safe energy sources. Many families living in isolated rural areas and informal urban settlements remain in the lower echelons of the energy ladder. The majority of these households continue to rely on rudimentary and traditional, inefficient solid fuels for cooking, lighting, and running electrical appliances. Even among those households connected to the central grid, many continue to use firewood as the primary energy choice (Goldemberg, 2000; Gaunt; 2004; Shackleton et al., 2006, 2007). This finding is confirmed in empirical literature and official data and information. (Davis, 1998; Thom, 2000; Madubansi and

Shackleton, 2006, Winkler, 2006; Chirwa et al., 2010; Matinga and Annegarn, 2013; Matsika et al., 2013; Stoppok et al., 2018).

The sustained high usage of firewood for cooking in rural areas, according to Shackleton et al. (2006, 2007), was closely linked to cultural rituals, traditions and behavioural characteristics. Certain cultural rituals require the use of specific tree species for ceremonial sacrifices and food cooking. Cooking traditional foods such as *umqusho* (dried, stamped and chopped white corn kernels and beans) and *umkhupha* (steamed bread) common in the Eastern Cape requires up to six hours of cooking. The GP and MAVT modelling results for informal urban areas also confirmed a preference for firewood among the poor.

The study revealed a partial understanding of the multifaceted nature of the energy consumption and access patterns among poor communities residing in rural areas and informal urban settlements identified in Section 2.2. User preferences in their energy source choices tend to be overlooked. In Chapter 2, it was also noted that the central grid extension was hailed as the "magic bullet" for boosting energy access and combating poverty among the poor, particularly in rural areas. This emphasis on rural electrification through the grid has been at the expense of affordable, clean and safer sources of energy that meet the same objectives as grid electricity.

According to Lhendup (2008), low-income households require very little power such as radios, mobile phones and television sets. This dovetails with the present study's findings from the GP and MAVT (refer to Figure 27, Figure 28) that show that energy access among low-income households should include renewable energy sources and traditional fuels. The study also revealed that there was no need to abandon traditional energy sources, as they still have a role to play because they are inexpensive and some are used for cultural reasons. The research suggests that without government support, it will take a considerable amount of time for poor communities to transition from elementary energy sources to cleaner and safer options.

In addition to costs, the study found that other technology-specific goals (such as reducing the amount of time required to collect fuels and maintain systems, as well as environmental pollutants) must be considered when making energy access investment decisions. While minimising drudgery is crucial for reducing poverty, spending less time on uneconomic activities directly increases the amount of time available for productive pursuits. Fuel collection is often seen as a woman's or young girl's responsibility (Dovie et al., 2004; Howells et al., 2005; Matinga and Annegarn, 2013). This has meant that women and young girls remain in

the throes of poverty, given the lack of access to education and productive and income-generating employment activities (Kaygusuz, 2010).

8.1.2 Literature review findings

The theoretical literature review observed that MCDA techniques are useful for solving complex decisions. These decision-support techniques are suitable for unravelling problems characterized as a choice among several alternatives. The study, therefore, confirmed the usefulness of MCDA decision-support techniques given their ability to decompose problems into smaller parts, the examination of each part and the integration of the parts to yield acceptable solutions. The research further established that, in group settings, MCDA techniques are useful in assisting stakeholders to a problem to engage collaboratively on a decision opportunity (the problem) and trade-offs among alternatives that permit all members to reflect the values that each participant views as imperative. The results of the present study agreed with these findings. The adoption of the augmented Chebychev and the MAVT techniques proved useful in unravelling and solving a problem with multiple stakeholders and several alternatives (refer to Chapter 6 and Chapter 7).

The empirical literature review showed an overwhelming weight of academic studies that demonstrate the usefulness of MCDA techniques to address the energy access problem among the poor. The inclusion of different stakeholders and different stakeholder preferences and criteria when evaluating projects strengthens the argument for application. The energy infrastructure planning problem and decision-making using MCDA techniques cover a broad range of areas of application in many countries. The studies confront the challenges of choosing policy options favouring different energy technologies for electricity generation in the US, UK, Germany, Finland, Paraguay, Tunisia, and Colombia.

According to the academic literature reviewed, two categories of techniques are available for solving multi-objective energy planning problems. The first category is comprised of techniques in which problems are solved using intricate multi-objective decision-making procedures, Section 4.3. The second category includes techniques in which complex problems are solved using simplified decision-making procedures incorporating even softer criteria, Section 4.4.

The empirical literature review also observed that no single MCDA technique could be considered superior to another. The nature and type of problem at hand, number of alternatives, number of stakeholders involved, type and availability of data, and criteria

considered influence the choice. This condition justified the development of problem-specific frameworks, such as the one employed in the present study (see Chapter 5).

The empirical literature review also established that existing studies using MCDA techniques to address energy access and planning problems primarily focused on solving the electricity supply problem. Studies that discuss energy supply problems for low-income and isolated rural settlements conclude that electrification underpinned by microgrids, and renewable energy technologies is the panacea for confronting the rural and low-income household energy problem.

As discussed in Chapter 6 and Chapter 7, results from the present study confirm the reviewed empirical investigations' findings, conclusions, and recommendations. The study's findings show that modern energy systems for low-income households should underpin energy supply choices ranging from firewood, bioethanol fuel, LPG, and microgrids underpinned by renewable energy sources, energy efficiency and energy storage.

A review of the rural and informal household energy supply status in South Africa in Chapter 2 and empirical literature studies reveals some thought-provoking developments parallel to the belief in rural electrification using the central grid. Many studies overlooked traditional and non-electricity-based energy supply systems that, in some way, meet the thermal, lighting and pumping needs of low-income households even without access to the electricity grid. In other words, the study found that energy policy analysis should be underpinned by a systematic approach that evaluates the entire energy system value chain.

8.1.3 Decision-making procedures

According to the findings, there is no definite evaluation criteria framework for ex-ante assessment of low-income family energy supply interventions, actions, plans, or policies in South Africa for any given objective or set of goals. This was enough to justify the development of a novel framework. The literature review revealed five primary evaluation criteria groups that are utilised internationally to assess low-income energy supply development programmes. These criteria groups include technical, economic, environmental, socio-economic and political. The present study disagreed with limiting criteria to these alone. Hence an expanded framework that combines both quantitative and qualitative criteria was developed.

As shown in Chapter 5, Chapter 6 and Chapter 7, results of the augmented Chebychev GP and the MAVT model implemented in this study demonstrated the need to include a broader range of criteria for effective decision-making. Additional criteria considered for the present

study expanded the suite of criteria to include safety, safety of supply, availability, efficiency, sustainability, feasibility, acceptability, health benefits, alternative use, and ease of use. As a result, it can be argued that using one-dimensional and single-objective models to support public-sector decision-making processes is insufficient. The necessity for homegrown solutions is supported by empirical evidence. To close this gap, the author developed a strategy that combines the GP and MAVT techniques and is built on Mintzberg et al. (1976) problem structuring paradigm (1976).

This study also implemented a novel procedure for evaluating and selecting both feasible and infeasible choices from the shortlist that emerged from the GP technique, combining two techniques, the GP technique coupled with the MAVT technique. The framework proved useful in solving an MCDA problem optimally using a consensus-driven and interactive decision-making process.

The GP technique allowed decision-makers, represented by a panel of experts, to establish several choices for the aspiration levels in at least one goal in the energy planning problem. The MAVT technique assisted in generating optimal portfolios of energy supply technologies to confront the energy access problem among low-income households.

8.1.4 Framework application and validation

Debnath et al. (2018) observed that most operational energy planning models used even in developing countries originate from developed countries. Decision-makers and stakeholders in these countries are concerned mainly with carbon emission reductions and enhancing energy security. Results from the applied energy planning framework showed that the framework introduced a novel way of guiding public sector officials seized with energy planning matters from a developing country perspective.

This present study provided a novel contribution to knowledge through a locally developed framework and by an author who has lived in the study areas. The MCDA framework developed for the study was useful under differing circumstances. Results from Chapter 6 and Chapter 7 showed that it is possible to develop an energy access model geared to solve the energy access problem for low-income households in rural and informal urban areas while at the same time accounting for carbon emissions. This finding dovetails with the climate change discussions currently taking place globally. On the other hand, energy planners and stakeholders are predominantly concerned with increasing energy access in many developing countries. Decision analysts, researchers and decision-makers could make use of the

portfolio-based policy planning framework developed for a developing country setting provided in Chapter 5.

8.1.5 Optimal portfolios of energy supply technologies for low-income households

One of the critical objectives of this study was the selection of an optimal portfolio of energy supply technologies for low-income households. The portfolios were built using the GP technique linked to a value function to integrate qualitative and quantitative objectives. In the final stage of the project, portfolio adjustment was applied to enable decision-makers to use their knowledge and experience to adjust the portfolio by adding or deleting alternatives.

It was observed that portfolios comprised of energy supply technologies with the least consumption of lifecycle financial resources were preferred. Secondly, portfolios with higher overall scores on qualitative criteria performed better overall. The typical viable and optimal strategy would be a policy option whose portfolio consisted of a combination of solar PV, wind and bioethanol fuel and with solar and wind forming part of a micro-grid catering for electrical needs. The study findings confirmed what has been reached from empirical investigations (Ramanathan and Ganesh, 1994, 1995); Doukas et al., 2007); Cherni et al., 2007); Lhendup, 2008); Silva and Nakata, 2009); Stein (2013) and Bueno-López et al., 2019). Cherni (2007) cautioned against the adoption of exclusive and cure-all solutions in an environment characterised by technological advancements.

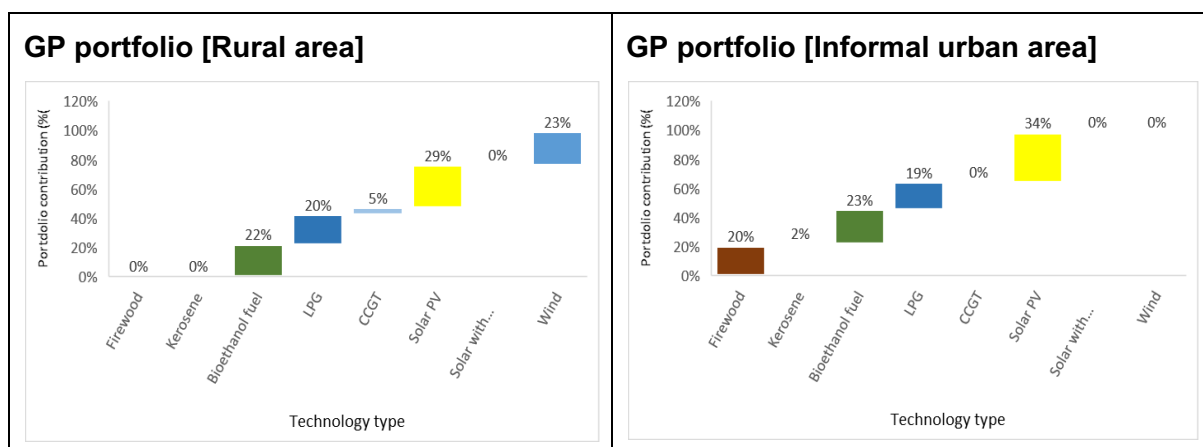
It is worth noting that a bioethanol fuel portfolio would be more sustainable if bioethanol fuel were produced locally. This will ensure that the community would benefit from the job creation potential of bioethanol fuel. Youth unemployment and underemployment are serious problems in South Africa and are often more severe in rural than in urban areas. White (2012) notes that “small-scale agriculture is the developing world's single biggest source of employment. With the necessary support, it can offer a sustainable and productive alternative to expanding large-scale, capital-intensive, labour-displacing corporate farming”. The portfolio would also be more successful if combined with a forestry management programme to ensure sustainable growth of bioethanol fuel and the planting of new trees. These GP and MAVT results are consistent with results observed in the literature.

The study established the goal of minimising upfront capital costs was an important one. The economics of energy supply technologies is evolving. For example, as shown under the three study scenarios, the cost of renewable energy technologies is improving, with significant reported declines in the cost of manufacturing and installing some technologies such as solar and wind as technical advances materialise.

The study observed that minimising the operational lifecycle costs was also an equally important goal. Renewable energy technologies are associated with near-zero fuel costs, making them cheaper from a lifecycle cost perspective. As highlighted above, this contrasts with rising costs for the conventional systems, primarily affected by increasing market-determined prices of fossil-based fuels (such as coal, gas etc.). Consequently, it is not surprising that the resulting optimised energy mix from the GP model and MAVT applications was made up of electricity from a micro-grid comprised of a combination of solar PV, wind and bioethanol and LPG and none for all other technologies considered.

The study established that poverty eradication interventions aimed at the poor in rural areas should not be limited to these areas only but also to low-income families living in informal urban settlements. The framework developed for the study was designed to cover different scenarios.. Figure 37 presents a graphical summary of the resulting energy portfolios obtained from applying the augmented Chebychev GP procedure in Chapter 6.

Figure 37: Summary of the Augmented Chebychev GP model results



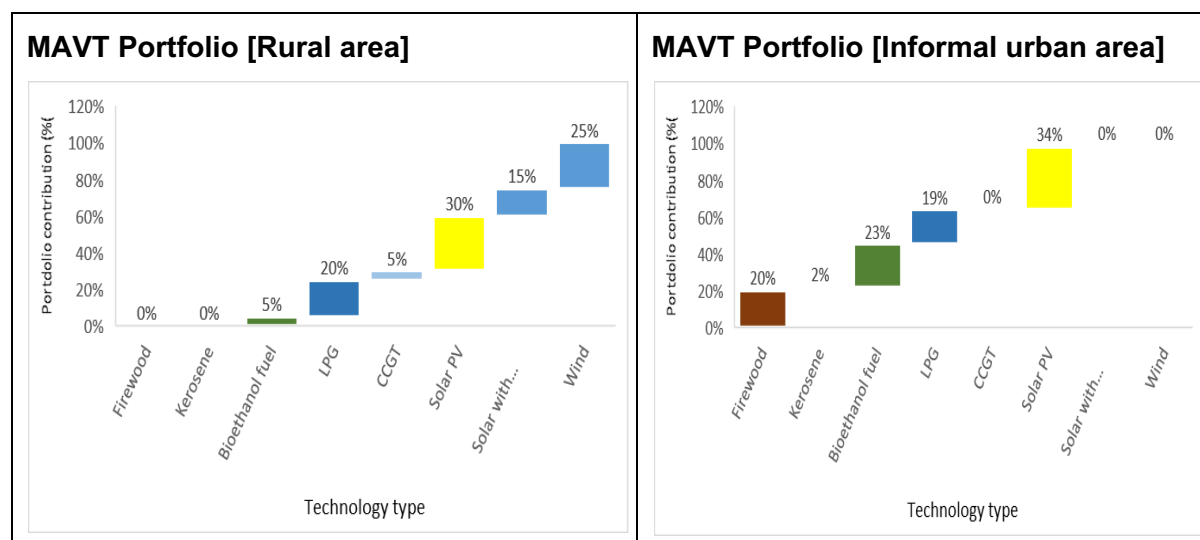
Source: Augmented Chebychev GP model

Notable differences between the MAVT results and the GP scenarios for informal urban areas are the high proportions of firewood under the technical scenario for informal urban areas. These differences can be explained by the inclusion of non-qualitative criteria such as safety and cultural considerations, which are included in the MAVT models.

The results imply that decision-makers should consider both quantitative and qualitative criteria, given the ever-increasing informal urban area populations and the expansion of informal settlements in South Africa in planning energy interventions. These populations are primarily people migrating from rural areas to informal urban areas and people who continue

to abide by cultural practices. Figure 38 summarises the energy portfolios obtained from applying the MAVT technique in Chapter 7.

Figure 38: Summary of MAVT model results



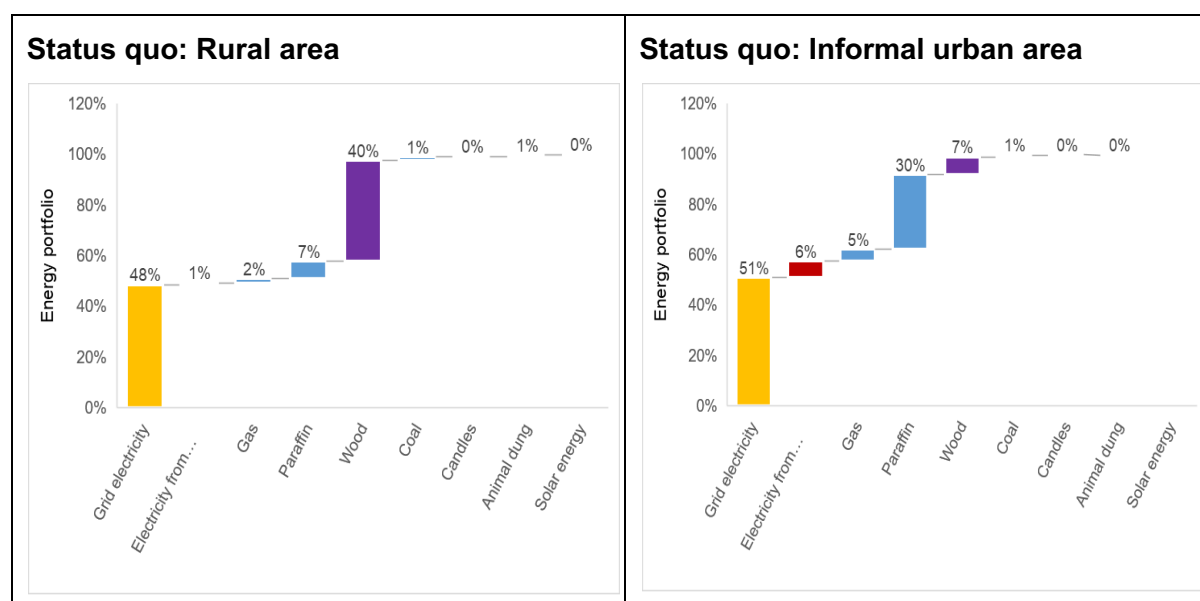
Source: MAVT model

Regardless of the differences between MAVT results and GP scenarios, as has been observed in the empirical literature (refer to Section 8.1.2 and Chapter 4), the study results show that rudimentary fuels such as firewood and kerosene, and central grid electrification, have no place in the energy mix for low-income households.

It is also worthwhile noting that despite the results of both the MAVT and GP models indicating that there is no place for firewood, firewood will nonetheless continue to be relied upon among the poorest, as posited in empirical investigations (Davis, 1998; Goldemberg, 2000; Thom, 2000; Gaunt, 2005; and Madubansi and Shackleton, 2006; Matsika et al., 2013; Shackleton, 2017). Figure 39 presents a summary of the current energy portfolios based on 2018 GHS data (Stas SA, 2019).

As discussed in Chapter 2 and as shown in Figure 39 (see also Section 2.4), firewood accounts for approximately 48 per cent of energy requirements for cooking in traditional dwellings and 51 per cent in informal urban areas. In the informal urban dwellings, over 30 per cent of households rely on kerosene and 7 per cent on firewood, respectively, for cooking. Around 40 per cent and seven per cent of households in traditional houses rely on firewood and kerosene, respectively, for cooking (Stats SA, 2019). The high use of kerosene in informal urban area dwellings is attributed to its affordability.

Figure 39: Status quo: energy portfolio for low-income households (cooking)



Source: Stats SA (2019)

This study shows how decision-makers can make decisions about both sources and uses of energy. It points to several overlooked opportunities that could be activated to help low-income households fully transition to greater use of and benefit from modern energy supply technologies. By focusing on poor communities and examining their energy portfolios, the researcher discovered previously overlooked opportunities that encourage the adoption and use of modern and improved energy sources.

The study results showed that there is an opportunity to enable continued and greater use of new energy sources. However, the affordability and reliability of these sources are barriers to continued and greater consumption. Few households could afford to solely use a new, improved energy source at desired levels. Most poor communities, it was also discovered, cannot afford to pay for ongoing operational costs on a regularly. Households accustomed to utilising free firewood or living without grid power may find it difficult to meet the new costs of R0.59 per meal for grid electricity and R1.32 per meal for LPG, respectively.

This study established that the expansion of the primary grid has not decreased the use of rudimentary solid fuels and paraffin for cooking. There is, therefore, an ample opportunity to grow the energy portfolios of rural households in beneficial ways through entirely new uses of energy, through the addition of cooling, small to medium refrigeration, heating and entertainment appliances. The study shows that there are strong linkages and trade-offs between goals. Synergies would need to be exploited further to maximise the quality of the decisions. At the same time, trade-offs would also need to be handled in a manner that results

in the development of a fully optimised portfolio. The projected declining costs of renewable energy technologies are likely to narrow the trade-offs between goals, particularly the minimisation of upfront capital costs and environmental goals that appeared at a tangent at the time of the study.

8.2 Policy implications

8.2.1 Overview of the current pro-poor energy policy setting

Since the introduction of the White Paper on Energy Policy in 1998, South Africa has seen a number of pro-poor energy initiatives. These policies guide access to affordable energy sources and improve governance among the various stakeholders. These policies and initiatives, as well as the entities in charge of implementing them, are listed in Table 21. The table is followed by detailed descriptions of various policies.

Table 21: Summary of current policy settings

Department	Implementing agencies and measures
Department of Mineral Resources and Energy (DMRE)	DMRE, Eskom - Integrated National Electrification Programme
	DMRE, Eskom, Municipalities - Free Basic Electricity Policy
	DMRE, Eskom, Municipalities - Free Basic Alternative Energy Policy
	DMRE, Eskom, Municipalities - Inclining Block Tariff
	DMRE, Municipalities - Non-grid electrification programme
	DMRE, Eskom, private sector - National Solar Water Heater Programme
Department Of Cooperative Governance and Traditional Affairs (COGTA)	COGTA, municipalities - Back to Basics Programme
Department of Environment, Forestry and Fisheries (DEFF)	Environment Forestry and Fisheries - Draft strategy for addressing air pollution in dense low-income communities of South Africa
World Bank Africa	World Bank Africa

Department	Implementing agencies and measures
	<ul style="list-style-type: none"> - Energy Sector Management Assistance Programme - Biomass Energy Initiative

a) Integrated national electrification programme

The INEP programme aims to provide universal access to affordable electricity. According to the DMRE, since its inception in 1994, the programme increased electrification rates, from 36% in 1994 to 87% in 2016 (DMRE, 2016). Because it was directly linked to the Reconstruction and Development Programme, the initiative was first focused on urban areas (RDP). The majority of households in formal urban areas have access to electricity except for those families living in informal urban areas. As the government seeks to keep up with the rapid rise of urban settlements, the growth of informal urban settlements has brought issues. Illegal electricity connections and cable theft have increased in informal communities. Municipalities, Eskom, and the government are all faced with the problem of illegal electrical connections (Seleka, 2021). Given the significant number of South Africans living in informal urban settlements, the current study included an informal urban settlement scenario and proposed pathways for expanding access to energy for families living in these areas.

b) Free basic electricity policy

According to the Energy Research Centre at the University of Cape Town, the success of the INEP programme was hampered by low usage of electricity due to affordability constraints (ERC, 2002). In 2002, the FBE strategy was implemented to aid the shift from inefficient and dangerous fuels to electricity (DME, 2005). The FBE policy is a subsidy that provides a free monthly allowance of 50kWh of electricity to low-income households. It was expected that the 50kWh allowance was sufficient to meet basic electricity needs such as lighting, powering of electrical appliances and water heating (Winkler, 2006).

According to the Stats SA (2017), the FBE has gone a long way in ensuring the transition to electricity among households connected to the grid. The programme is implemented at the sub-national level and is funded by fiscal transfers. . Implementation challenges at the municipal level and lack of data make it difficult to determine how many people have benefited from the subsidy and the effectiveness of the policy.

c) Free basic alternative energy policy

In 2007, the government introduced the FBAE policy to assist unelectrified households with subsidised alternative energy (DME, 2007). The FBAE policy enables municipalities to supply

off-grid energy to indigent households. Policy energy supply options include candles, kerosene, LPG, bioethanol fuel, solar home systems and coal. Unfortunately, this policy is not geared to benefit families living in informal urban areas.

According to the Non-financial census of municipalities report of 2018 (Stats SA, 2018), out of the 213 local and metropolitan municipalities in the country, 49 indicated that they supply indigent households with at least one form of basic alternative energy source under the FBAE policy. Most of the municipalities are located in the Eastern Cape and Northern Cape, and the North West province. The Non-financial census of municipalities reports of 2018 (Stats SA, 2018) also notes that JB Marks Local Municipality in the North West is the only municipality that supplies LPG as an off-grid solution. The municipality also provides the most options (i.e. LPG, kerosene, candles and solar).

d) Inclining block tariff policy

The government adopted the Inclining Block Tariff (IBT) in 2010 to further protect the poor from rising electricity tariffs. The strategy was designed as a subsidy scheme, with the utility's tariff being linked to usage levels. The tariff was created to subsidise the electricity tariff for low-energy-consumption families; the tariff rises as consumption rises..

The rationale behind this policy was that low-income households consume a smaller amount of electricity than other households due to the lack of high energy-consuming appliances. The non-payment of electricity bills has further complicated the policy's success even by subsidised households and the inflation tariff increases that the country has witnessed over the years. The efficacy of the intervention has been hampered by the high levels of informal and illegal connections (Seleka, 2021).

e) National solar water heater programme

The National Solar Water Heater Programme (NSWHP) was launched in 2009 under the aegis of the National Energy Strategy, the White Paper on Renewable Energy, and reinforced by the central role identified for solar water heaters in the National Development Plan (NDP). The programme started as a demand-side management project in response to the national electricity generation constraints but shifted to a social programme with additional objectives of mitigating adverse climate change (through a reduction in CO₂ emissions), protecting the poor from electricity tariff increases, facilitating local manufacturing industries and employment creation.

Since its commencement in 2010, the initiative has faced numerous implementation obstacles (institutional, financial, and technical). Despite the lack of formal confirmation, preparations were in the works in 2021 to restart the initiative, with procurement and installation functions being centralised at the DMRE and the Government Technical Advisory Centre (GTAC) serving as a strategic partner. GTAC participation is expected to increase the capacity to roll out the programme. It is expected that owing to economies of scale, centralisation of procurement will result in lower the cost at which the solar water heaters can be procured.

f) Non-grid electrification programme

Realising the challenges of connecting rural households to the grid, the government launched the non-grid electrification programme in 1999. The programme, designed as a public-private partnership, involved the government contracting the private sector through concessions to deliver non-grid electricity to unelectrified rural communities under a fee-for-service model. Under the model, the concessionaire would act as a licenced utility, owning the electricity generation assets and supplying electricity at an agreed tariff to be paid by the customer. The programme aimed to install 350 000 solar home systems based on PV technology with a 50-watt capacity.

The non-grid electrification initiative has been challenging to take implement. The model's economics render the provided electricity unaffordable for the intended recipients. The eligibility criteria (proof of residence, proof of employment, bank statements and demonstrable ability to make monthly payments) also made it difficult for poor households to participate in the programme. Nonetheless, the government decided to subsidise the monthly service fee (the equivalent of the basic electricity support service tariff (BESST) was expected to increase uptake. It has, however, been observed that even after a capital subsidy and the poverty tariff, low-income households would still not afford to pay for the electricity, let alone buy the electrical appliances.

g) Back to basics programme

According to CoGTA, despite registering some achievements in improving the livelihoods of the poor, much still needs to be done to support and enforce the implementation of the local government mandate for service delivery (CoGTA, 2014). CoGTA has been seized with introducing interventions to transform the local government sector. These interventions include the establishment of the Municipal Infrastructure Support Agent (MISA) and the Back to Basics Programme. CoGTA established MISA in 2012 to develop the capacity of municipalities to deliver and manage infrastructure sustainably.

Launched in 2014, the Back to Basics Programme was aimed at supporting the NDP by increasing the capacity of municipalities to better serve rate-payers and residents. The intervention package includes support for improved service delivery through improved infrastructure maintenance and ensuring the provision of FBE and maintenance of the indigent register (CoGTA, 2014).

h) Biomass Energy Initiative

The Biomass Energy Initiative for Africa falls under the purview of the World Bank Africa Energy under its Energy Sector Management Assistance Programme with additional funding from the Africa Renewable Energy Access Trust Fund. The initiative aims to foster sustainable development in Africa by ensuring universal access to clean energy. The Biomass Initiative focused on a wide range of technologies ranging from charcoal to briquettes and high-efficiency cookstoves to bioelectricity, social enterprise and public-private partnerships.

In South Africa, the Biomass Energy Initiative for Africa was launched with a focus on the promotion of improved biomass rocket stoves. It was expected that the intervention would reduce reliance on forests for traditional biomass.

i) Draft strategy for addressing air pollution in dense low-income communities of South Africa

According to the DEFF, several densely populated low-income communities do not comply with National Ambient Air Quality Standards. This means that people living in those communities continue to be exposed to harmful pollutants, particularly in winter resulting in adverse health impacts for adults and children. The department acknowledged that fossil-based fuels (coal, wood, and kerosene) were one of the leading contributors to poor air quality.

In response, in 2016, the Cabinet of South Africa approved the draft Strategy for Addressing Air Pollution in Dense Low-Income Communities of South Africa. The strategy aimed to address the high levels of air pollution in densely populated, low-income communities. According to the DEFF, this will be achieved by strengthening existing policy instruments to reduce air pollution. These instruments include stringent emissions standards set in terms of the Air Quality Act 39 of 2004 to control industrial emissions, alternative energy strategies implemented by DMRE and subsidised clean energy alternatives.

The draft Strategy will facilitate a coordinated approach to implementing interventions aimed at reducing pollution associated with the burning of “dirty fuels” by low-income households. The DEFF reckons that coordination is given the role that several organisations will have a

role to play in reducing emissions among low-income communities. Key role players identified in the draft Strategy include the DEFF, DMRE, Department of Human Settlements, National Department of Health (NDOH) and Department of Science and Technology (DST), respective provincial departments, municipalities, industry, non-governmental and community-based organisations.

8.2.2 Outcomes of the existing policies and programmes

The major policy developments discussed above are a response to the growing sense of urgency in ensuring access to affordable, clean and modern sources of energy among the poor by the government. However, a review of the policies indicates that the current suite of government policies and programmes aimed at fighting energy poverty have produced sub-optimal solutions (see Figure 39). These policies and programmes have largely failed to address the problem of low energy access, given the high numbers of low-income families that continue to languish in energy poverty across the country. While grid electricity consumption is high in homes located in formal areas, the many households living in traditional and informal dwellings continue to rely on firewood.

It is clear from the discussion thus far that despite the numerous government interventions over the years the use of firewood and kerosene for heating and cooking will remain high in traditional and informal dwellings (see also Shackleton et al., 2007). In line with the study findings, one way to manage the unsustainable collection and use of firewood is the adoption of clean, energy-efficient firewood cookstoves (See also Chirwa et al. (2010). The country still grapples with high levels of energy poverty. Thus if the country is to achieve a reduction in energy poverty and reach its goal of universal access to energy, then policy and regulatory frameworks and resources to support energy service delivery need to be urgently and constructively reviewed.

8.2.3 Policy implications

This section discusses the implications of the study results on the existing pro-poor energy strategies and policies in South Africa. The discussion is organised around key themes that emerged from the analyses: defining the indigent customer, improved access to clean and affordable energy; regulation and environmental protection; empowering women and girls for inclusive development; sustainable and efficient use of natural resources; and the social contract.

a) Defining the indigent customer

In South Africa, the absence of a proper definition of indigent customers has rendered programmes such as the SHS, FBE and FBAE inoperable. Associating the term indigent with low-income households living within formal municipal boundaries and listed on the municipal indigent register has resulted in the provisioning of free electricity in rural areas excluding more impoverished families living in informal urban areas. In any case, in most rural municipalities, FBE and FBAE funding are not included in IDPs (Koelble and LiPuma, 2010). DMRE statistics suggest low uptake, as most rural households prefer grid electricity to off-grid systems for several reasons.

b) Improved access to clean and affordable energy

As the discussion in Chapter 2 highlights, in addition to job opportunities and financial resources, the main challenge facing low-income families in rural South Africa is access to modern, clean, and safe energy sources. The early phases of policy reform in the country post-1994 focused on improving access to electricity. This focus was underpinned by the belief that access to electricity was the panacea to ending poverty and addressing imbalances that existed at the time (refer to Sections 2.2).

The majority of households in low-income communities continue to rely on rudimentary and traditional, inefficient fossil-based fuels Figure 39. While some scholars argue that the situation is unlikely to ameliorate given the cultural dynamics associated with fuel use, the scarcity of fuelwood will likely force households in low-income areas to switch to cheaper modern fuels. The GP and MAVT formulations show that firewood, kerosene, and bioethanol fuel still form part of the energy mix for informal urban areas. This suggests that complementary policy instruments, such as the enforcement of environmental protection and deforestation regulations, should enable the required shift to cleaner fuels.

c) Regulation and environmental protection

Initiatives such as the FBE, the FBAE and IBT appear to offer indirect financial assistance to ensure access to affordable electricity; nothing is being done on the regulation side to discourage the continued use of fossil-based fuels. While the initiatives mentioned above have resulted in increased access, many poor households still do not have access to energy. The continued support for fuels such as candles and paraffin will likely impose additional financial and health costs on the beneficiaries of such schemes. Inevitably, these costs will be passed on to the fiscus and the taxpayer.

The findings in this research also support this claim, particularly that without government support, given the high upfront costs associated with renewable energy sources, it will take a considerable amount of time for poor communities to transition from rudimentary sources of energy to cleaner and safer options. Decision-makers in South Africa could also consider the role of regulation when formulating policies to improve access to clean and affordable energy.

d) Technological advancement

Past technologies underpin most existing energy infrastructure. In light of the predicted climate change events, which are likely to increase in their severity and frequency, technology choices implemented today will become legacies in the future (refer to Chapter 6). This further supports the prominence of considering the implications of technological developments over the life span of deployed technologies.

Several technologies, such as fuel cells, are still maturing. These technological advancements would increase the efficiency of energy generation and consumption systems together with reduced lifecycle costs over time. In addition, most emerging energy generation technologies are largely environmentally friendly. Therefore, it is important to consider the total lifecycle costs of technologies when making investment decisions. Decision-makers should be aware of the fact that significant up-scaling and deployment of renewable technologies is critical for the realisation of the expected cost reductions. This information would assist the DMRE in reconfiguring policies and scenarios for initiatives such as the non-grid electrification programme.

As the scenarios in Chapter 6 and Chapter 7 suggest, an alternative approach to increasing energy access to low-income communities in the age of technological advancement would be to develop climate-proof portfolios anchored on the micro-grid model that are most appropriate for a specific community. The electricity sector, especially Eskom, would benefit from a greater understanding of the impact of decentralised micro-grid systems on existing centralised infrastructure. For example, the planning of transmission lines and supporting ancillary infrastructure would need to be reconfigured to account for the emergence of decentralised micro-grids.

e) Empowering women and girls for inclusive development

If allowed to continue and nothing is done to energy mixes, the status quo implies that gender disparity, especially in low-income communities, will persist. (refer to Section 1.1 and Section 6.7.3) The lives of women and girls will continue to be characterised by a lack of access to

education and productive and income-generating employment activities, further entrenching gender inequality (Dovie et al., 2004; Howells et al., 2005; Kaygusuz, 2010; Matinga and Annegarn, 2013; Urge and Feyisa, 2019). This directly contradicts other government-led initiatives and policies to empower the girl child and women to ensure a just transition and inclusive and sustainable development. According to the International Institute for Sustainable Development (2021), “a just transition approach ensures that the affected people are considered by those making decisions”.

Technology is helping advance modern society in fundamental ways. Adopting portfolios generated from the study in Chapter 7 and Chapter 8 should go a long way in reducing the burden placed on women and girls. This will open opportunities for women and girls to pursue studies and engage in productive economic activities.

f) Sustainable and efficient use of natural resources

In this research, strategies that improve society’s well-being through various policy interventions may be supported by investments in energy efficiency both in terms of generation and consumption. Therefore, this research argues that behaviour changing strategies, such as energy efficiency interventions and educational awareness programmes and strengthening existing policy instruments to reduce air pollution, have a significant role in the future. These should continue to receive government support. However, Chapter 8 suggest that efficiency losses in other areas may easily override efficiency gains in one area. This further substantiates the need for an integrated approach to policy development and implementation in line with recommendations made under the draft strategy for addressing air pollution in dense low-income communities of South Africa.

g) The social contract

Concomitant with the evolution of the national policies (refer to Table 21), there has been a trend towards the decentralised supply of energy, such as by the use of embedded generation. This means that end-users will influence the selection of technologies over time. Therefore, it is important to promote strategies that support the trend toward decentralisation of energy services to avoid trade-offs.

An example already discussed above is the adoption and installation of solar home systems under the auspices of the FBAE and the non-grid electrification programme. As mentioned in Section 7.2.7, these interventions should be supported by initiatives that make low-income

communities aware of environmental issues affecting their well-being, such as pollution, implications of drought and now climate change.

8.3 Study conclusions

The study concludes that given the continued use of fossil-based fuels among low-income households in South Africa, comprehensive energy interventions based on different energy fuels are needed to address the energy access problem and achieve broader socio-economic goals. Furthermore, the research concludes that the approach adopted needs to consider the aspirations of different actors to a problem instead of a one size fits all approach.

The research concludes that MCDA techniques are useful for solving complex decision opportunities (problems) characterized as a choice among several alternatives. They force the decision-makers to think, inquire, fine-tune, test, and focus on what is important logically, consistently and iteratively (see Figure 12). The investigation further concludes that, in group settings, MCDA techniques are useful in assisting stakeholders to a problem to engage collaboratively on a decision opportunity (the problem) and deliberate on trade-offs among alternatives in a manner that permits all members to reflect the values that each participant views as imperative.

The research also concludes that no single MCDA technique can be considered superior to another as their use depends on the circumstances and decision. There are many ways in which the different MCDA decision-support techniques can be used complementarily, and each can supplement the shortcomings of the other in real-life applications. The MCDA framework developed and applied in this study is based on a combination of two MCDA techniques.

The analysis shows an overwhelming weight of academic studies that demonstrate the use of MCDA techniques to address the energy supply problem. A key observation from the literature review was that the application of MCDA on its own is often subjective. At the same time, it is also mathematically challenging to find Pareto-optimal solutions while at the same time accounting for multiple objectives in combinatorial problems. This limitation hamstrings several studies reviewed.

The empirical review observed that the latest trend in decision theory is the combination of two or more techniques to make up for shortcomings in any particular technique (Stewart and Scott, 1995; Buchholz, 2009; Streimikiene et al., 2012; Rojas-Zerpa and Yusta, 2015). This condition justified the development of the problem-specific framework employed in the present

study (see Chapter 5). The framework developed for the study establishes a novel and universal agenda for assessing the quality of energy access development plans. Energy planning authorities and decision-makers in the energy sector can also adopt this framework to overcome significant challenges in implementing energy access strategies.

The research concludes that an energy portfolio comprising bioethanol fuel for cooking and heating combined with a micro-grid made up of CCGT, solar PV, solar with storage and wind in rural areas of the country can contribute more meaningfully to the attainment of energy access goals and spurring economic development that benefits the poor. Similar interventions have resulted in substantial benefits to poor communities (Mandri-Perrott, 2010).

In cases where firewood continues to be used, particularly during the transition phases, cooking systems and cookstoves should have enclosed compartments to ensure the efficient burning of firewood. This covering will result in less firewood required to generate energy. Ultimately, the controlled burning of fuel should result in reduced fuel costs, time savings, and environmental and health benefits arising from reduced exposure to HAP (Le Roux et al., 2009; Dresen et al., 2014).

It has been observed that there is a strong relationship between energy access and economic development and prosperity (Van der Kroon et al., 2013). Access to energy enables communities to engage in productive economic activities. Access to modern and renewable energy sources such as solar catalyses the establishment of businesses to promote district-based development. Such development should help reduce rural-to-urban migration, which is problematic and has resulted in the mushrooming of informal settlements in towns and cities.

The study concludes that cultural barriers, rituals, and perceptions prevent communities from adopting new energy sources, including renewables. As a result, communication strategies must be developed and implemented to ensure acceptance to ensure the seamless adoption of energy supply technologies proposed in this study. These incentives to be communicated include increased health incomes, reduced overheads, more free time available for productive activities and other valuable aspects to a community.

The study challenges the South African government's discontinuation of initiatives such as the Biomass Initiative, safety campaigns for safe use of kerosene and emphasis on grid-based electrification expansions to increase energy access. A full understanding should inform any programme aimed at increasing energy access of the targeted beneficiaries before the crafting

of interventions. If implemented correctly, improved energy access systems should result in the achievement of developmental goals in an inclusive manner.

8.4 Recommendations for policy and practice

Despite the development and execution of the significant policies and strategies listed in Section 8.3.1 (see also Table 21), their success has yet to be shown, and many low-income communities' livelihoods have not been transformed. It appears that these policies and programmes have produced sub-optimal solutions. Erratic rainfall patterns extended dry periods, and drought, which already forms part of South Africa's climate, are likely to increase in severity in future years under climate change. Therefore, policymakers must take considered action to resolve the current practice that fails to address energy poverty before it becomes a matter of urgency with far greater ramifications at far greater costs

This section provides recommendations for consideration that would assist in improving the planning, development, implementation, coordination and integration of energy policies that benefit the poor in South Africa. Chapters 2 to 7 and earlier sections of this chapter form the basis of the recommendations. The recommendations align with the study objectives summarised in Figure 1 (Methodological framework for the present study) to provide focussed policy inputs for decision-makers. The recommendations refer to the government measures listed in Table 21 and the results of the MCDA framework developed and implemented.

8.4.1 Recommendation 1: The evolution of the rural energy supply in South Africa

The continued use of traditional and polluting solid fuels and kerosene in open fires and inefficient cookstoves in poor households (see Figure 39) suggests that electrification investments would achieve meaningful developmental benefits if combined with modern sources. Chapter 2 findings indicate that there is a need for an approach that considers the aspirations of different actors to a problem as opposed to a one size fits all approach. As outlined in Chapter 2, Section 2.6, energy policy reforms are currently driven by national reform agendas (RDP, Growth, Employment and Redistribution and the NDP) and implemented by the national department. This research, therefore, suggests that policy integration be considered at both the national, provincial and sub-national levels. Recommendations to assist with policy planning, development, implementation, coordination and integration of energy policies that benefit the poor in South Africa now follows:

- The study recommends that when making investment decisions aimed at extricating the poor from further poverty, the costs of running the installed system should be lower for the beneficiary to ensure affordability. Any intervention that results in high recurring

energy bills will inevitably push the poor into further poverty. This will result in either the government having to step in to cover the bills through fiscal transfers or the low utilisation of the installed systems rendering the intervention sub-optimal. The low electricity usage among low-income families with access to grid electricity typifies the conclusion. Apart from electricity bills, beneficiaries are expected to buy electrical appliances, which are usually beyond the reach of many given their low-income levels (Bhorat et al., 2012; Stats SA, 2019).

- The study recommends minimising drudgery as a key objective in energy planning among the poor, as this is one of the avenues available for fighting gender inequality in South Africa. Gender issues still plague South Africa. According to the World Economic Forum's Gender Gap Index, South Africa ranks 19 out of 149 countries (Schwab et al., 2017). Decision-makers also need to integrate environmental goals when crafting energy access interventions. Environmental considerations include decisions concerning the reduction of household air pollution. The present study dealt with an energy access decision to substitute high polluting fuels with cleaner fuels to promote healthy living among the poor. By implementing environmental management, low-income communities can achieve both direct and indirect benefits. Reducing indoor household air pollution means better health outcomes, and reduced hospitalisation is a direct benefit. Reducing social costs, such as environmental pollution and natural resource depletion and creating an eco-friendly image, is an indirect benefit
- The central government manages energy policies and strategies summarised in Table 21 by the DMRE, with implementation overseen by municipalities at the sub-national level. The existing institutional arrangement does not readily support the timely implementation of the policies and strategies. A recommendation, therefore, is to follow principles laid out in this study which are based on MCDA and problem structuring techniques discussed in Chapter 2 (Refer to Figure 12). This can be achieved by establishing a multi-stakeholder task force on energy access by poor households to ensure an integrated approach to policy development and assist with the coordination of energy policies between the national and local governments. Recommended task force members include DMRE, CoGTA, MISA, respective provincial departments, and municipalities. Possible activities of the task force would consist of:
 - Ensuring that policies crafted at the national level and implemented at the local government level are translated and fully integrated.
 - To develop regulatory arrangements that ensure adherence to regulations.

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- Similarly, coordination is also recommended at the national level. As the name suggests, the DMRE is responsible for implementing the energy reform agenda at the national level. In the case of pollution, DEFF develops and enforces environmental protection laws. This research recommends increased coordination and the establishment of a similar task force on energy access by low-income households. Recommended stakeholders include comprised of officials from the DEFF, DMRE, Department of Human Settlements, NDOH, National Treasury, Eskom, the Presidency through Infrastructure South Africa, DST, respective provincial departments, and municipalities, industry, non-governmental and community-based organisations with CoGTA and DMRE as the joint secretariats. These can be developed by following steps established in this study on establishing panels. Possible activities of the task force would include:
 - Ensuring an integrated approach to policy development.
 - Development of regulatory arrangements that ensure adherence to regulations.
 - Ensuring stakeholder involvement through the decision-making stages. As discussed in Chapter 3 and Section 7.2.7, it is essential to involve stakeholders using both top-down and bottom-up techniques.
 - Ensuring consensual policy making to force different stakeholders to work together collectively rather than unproductive opposition.
 - The motivation for this recommendation is that implementing integrated, coordinated and consensus-driven policies and strategies will result in the maximisation of synergies and minimisation of duplications. This is evidenced by the resulting portfolios generated by the augmented Chebychev GP and MAVT models discussed in Chapter 6 and Chapter 7. This was a vital aspect of this study.

8.5 Recommendation 2: The use of MCDA techniques in rural energy infrastructure planning

The literature review and the results obtained from the GP and MAVT models showed that no single MCDA technique could be considered superior to another as their use depends on the circumstances and decision to be made. This, therefore, suggests that there are many ways in which the different MCDA decision-support techniques can be used complementarily and that each can supplement the shortcomings of the other in real-life applications.

The study challenges the many studies reviewed during the empirical literature investigation that overlooked traditional and non-electricity-based energy supply systems that, in some way, meet thermal, lighting and pumping needs of low-income households even without access to

the electricity grid. Therefore, the study recommends that energy policy analysis be underpinned by a systematic approach that evaluates the entire energy system value chain accounting for both traditional and modern sources of energy.

The study also recommends that given that there is no single multi-objective or MCDA technique that can be considered superior, decision analysis and decision-makers ought to combine two or more techniques during the decision-making process to make up for shortcomings in any particular approach. This trend has been observed in the literature. The current study results testify to the robustness of combining techniques, especially those that account for quantitative and qualitative criteria.

8.6 Recommendation 3: The need to develop a novel decision-making procedures

Based on the literature review and the results obtained from the GP and MAVT models, the study recommends that energy planning authorities and decision-makers in the energy sector adopt frameworks similar to the one developed for the present study. This will go a long way to improve energy access development plans to benefit low-income households, identify the defects in the policies and processes, and achieve the developmental objectives of such policies. The framework developed for the study established a novel and universal agenda for assessing the quality of energy access development plans. Energy planning authorities and decision-makers in the energy sector can also adopt this framework in its current form to overcome significant challenges in the implementation of energy access plans.

8.7 Recommendation 4: The optimal energy supply portfolio for low-income households

Results obtained from the study support the continuing emphasis on the suitability of the GP and MAVT techniques for optimising objectives relating to competing activities in energy planning and subject to resource availability through the use of mathematical GP and value functions. This section makes recommendations based on the portfolios generated by the augmented Chebychev GP and MAVT techniques in Chapters 6 and 7 (see also Figure 37 and Figure 38), as well as the current energy portfolio for low-income dwellings derived using 2018 GHS data (Stats SA, 2019). It is expected that these measures would increase the consideration of new ideas and modification of existing measures.

- In the short term, given the presence of biofuel and firewood in some of the study's scenarios and the current energy mix for the poor, government-supported programmes like the Biomass Energy Initiative should be revisited, supported, and adopted by the government based on the findings of the literature review. The research conducted

revealed that traditional firewood is an important source of energy for cooking in poor communities. Firewood is freely available in many rural areas. Therefore, the use of firewood is recommended for wooded and wet areas where firewood can be collected freely with minimal damage to the environment. (refer to Section 6.5). The Biomass Initiative was discontinued in 1996, owing mainly to a lack of support for the project from the national department, which favoured grid electrification at the time (Marquard, 2006).

- Also, as the energy transition unfolds in the short term, urgent safety campaigns on the safe use of kerosene, which remains common in informal urban settlements (Francioli, 2020), are recommended. Kerosene accounts for considerable bodily injury and property damage affecting over 200 000 people every year in South Africa (Kimemia et al., 2014). The support needed included budgetary support for safety campaigns such as those run by PASASA, now the Household Energy Safety Association of Southern Africa (HESASA). Most low-income communities remain oblivious of the safe use of kerosene (Matinga, 2010). The MAVT model result for informal urban areas showed that kerosene would still account for two per cent of the energy mix in these areas. Budgetary constraints, lack of human resources, and formal engagement structures in rural and informal urban settlements have hamstrung the previous campaigns. Support from the SABS is also required to ensure that prominent kerosene stove brands such as the Panda meet the minimum standard safety requirements. In the long term, in line with the findings of this study, strategies aimed at replacing illuminating paraffin cookstoves and heaters with bioethanol fuel and LPG is recommended.
- Given the presence of solar, wind and LPG in the resulting energy mix for all the GP and MAVT scenarios, this research suggests that measures to support localised and distributed micro-grids as a means to reduce the reliance on the central grid for the supply of electricity supply should be supported. However, given the political appeal of electricity, it is unlikely that the current focus on grid-based electrification will cease soon. The government could achieve the same political goal through investments in community-based micro-grids that offer the same appeal as grid electricity.
- As identified in this research, energy efficiency offers significant advantages and can readily offset the requirement for investment in new generation of energy. Measures to support energy efficiency through demand-side management intervention, according to the study, should be supported. Numerous government measures

promote energy efficiency among low-income communities. These measures include the NSWHP.

- The central government has allocated significant support for developing alternative energy technologies. As outlined in Table 21, the DMRE administers the FBAE policy, the non-grid electrification programme and the NSWHP. The DMRE could consider introducing life-cycle cost criteria to ensure that only affordable technologies for low-income communities over their lifespan are supported. This could be determined by looking at the life-cycle costs of different generation technologies, such as those quantified in this study. Based on the results in Chapter 6 and Chapter 7 and the status quo, there is a strong case for encouraging investment into portfolios of energy comprised of bioethanol fuel, LPG, solar and wind because of their relatively low lifecycle costs, which translate to affordability. There is an opportunity to enable greater use of modern energy supply technologies bearing in mind the affordability and reliability which act as barriers to greater use.
- Planners seized with formulating and implementing government policy in South Africa are encouraged to reconfigure the current energy grant and subsidies regime in favour of interventions that result in immediate impact. For instance, instead of spending billions of rand on subsidised paraffin for indigent households, the same resources can be utilised to deploy bioethanol distribution infrastructure. Unlike paraffin, biofuel is cleaner and locally produced, implying local job creation and import substitution. Adding solar PV to the mix will help cater to these indigent families' electricity needs.
- This research recommends that mitigation of adverse climate change potential of technological options need to form part of the assessment criteria for policy scenarios. Climate change is likely to reduce water availability in many parts of South Africa. As discussed in Chapter 6 and Chapter 7, the IPCC (2016) predicts 20 per cent more drought months in most African countries by 2030.
- In line with the study's findings on users' reluctance to adopt modern energy sources for cultural reasons, especially in isolated rural areas, the study suggests that additional approaches are needed to ensure sustainable collecting and use of firewood. These approaches include promoting efficient cookstoves, promoting afforestation at a community level and the design of modern cooking systems that mirror traditional cooking methods. The study proposes that more thought should be given to the technical design and user acceptability of efficient cookstoves in urban and rural areas.

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- In addition to the measures mentioned above, the DMRE, in collaboration with the NDOH, DEFF, and other relevant state and non-governmental organisations, may consider educational awareness programmes for community members that emphasise the importance of energy efficiency and resource conservation as a means of environmental protection. Such an initiative would greatly assist in changing behaviour towards energy consumption in the longer term. The basis for this recommendation is that the provision of subsidised energy by the government and illegal and informal electricity distorts the true value of energy in South Africa.
 - The study solution for the isolated rural areas scenario may be dismissed as artefactual when, in fact, they point to real areas of concern. For example, given the lack of awareness in rural areas about the benefits of LPG (time-saving, health and environmental), LPG is perceived as unsafe. Low literacy levels are also another obstacle, as illiterate people tend to prefer their traditional practices and be resistant to change. Therefore, efforts should be invested in education and awareness campaigns to ensure that communities are informed about the benefits of clean fuels and sustainable use of fuelwood. Through accredited community health workers, the health sector is one avenue available to channel educational information on clean fuels and health.
 - Lastly, linked to the GP and MAVT model results, getting people out of informal structures and into well-built formal homes is one avenue available in the fight against poverty. There are various initiatives to roll out subsidised low-cost housing supplied with energy based on the study's recommended portfolio. From an energy and poverty perspective, bricks and mortar home should be the objective. Again, this entails the DMRE working in collaboration with the Department of Human Settlements and other state organs to plan, finance and implement housing programmes with clean energy access and built-in energy efficiency technologies (See also Martinaitis et al., 2007).

The development of energy policies will need to consider a range of factors and inputs. The recommendations outlined in this chapter represent one such set of inputs. Based on a comprehensive review of the energy policy and energy access by low-income communities in South Africa, the recommendations identify several opportunities at national, provincial and local government levels to improve the integration and coordination of energy policies.

It is also worth noting that long-run trends in energy access and energy transition strategies have profound long-term implications for a country in socio-economic development. Therefore, there is a need to promote energy supply technologies that will result in the attainment of

decision-maker goals and the SDG 7 goal of “ensuring access to affordable, reliable, sustainable and modern energy for all.” There is an opportunity to grow the energy portfolios of rural households in beneficial ways through entirely new uses of energy, such as refrigeration..

8.7.1 Strategies for defending the decisions

The study recommends several strategies for defending the decisions to citizens, taxpayers, government officials, press and political principals. These strategies include:

- Consensus is a prerequisite for the successful initiation, development and implementation of strategies in the public sector. Stakeholders in policy development should cultivate a sense of joint ownership over policies and help build consensus over both the need and the relevance of interventions. Decision-makers need to ensure stakeholder involvement throughout the decision-making process, and this ought to be done iteratively(refer to Chapter 3, Figure 12, Section 7.1 and Section 7.7.2).
- Related to the consensus-driven processes, decision-makers are encouraged to formulate clear objectives of proposed interventions. Policies are more likely to succeed if their intentions are focused and well defined rather than ambiguous. It is also necessary to avoid strategies advocated mainly by powerful minority groups.
- The study also recommends the incorporation of policy experimentation and the recourse to pilot schemes. Given their temporary nature, this strategy can prove powerful in testing out policy proposals before resources are committed. Policy experimentation facilitated by the national departments in selected provinces is a recommended approach in South Africa.

In implementing the framework developed for the study, the author recommends consensus-driven policymaking as one of the avenues to improve the adoption and support of policies emerging from the jointly agreed strategies.

8.8 Significance of findings, conclusions and recommendations - new knowledge generated

The study observed that South Africa’s crippling electricity problem makes energy a hot topic in the country. Energy access is an issue that most South Africans are deeply concerned about. A critical challenge for all decision-makers wrestling with energy poverty and poverty, in general, is how to assess which strategies and policies and establish which one works in practice. A corollary to this challenge is identifying a range of strategies that work

simultaneously, satisfying different goals and interests of different stakeholders. Methodological challenges include the development of adequate quantitative and qualitative energy modelling techniques to confront the energy access problem in a countrywide framework.

An even greater challenge is the knowledge and insights generated from decision modelling to find their way into the decision-making process. In this context, the present study explains how expanding the model developed to real-life problems can form the foundations of an improved approach to energy planning by decision-makers and practitioners in energy planning and policy formulation.

The continued use of one dimensional and single objective models has been proven not to be ideal in the modern world. The continued bickering over large scale programmes such as the nuclear build programme for South Africa confirms the challenge. Most energy access interventions (Table 21) implemented in rural areas have not been informed by sound and inclusive processes. The result of relying on one-dimensional techniques has been the delayed project implementation and the development and implementation of sub-optimal solutions. Those projects that have been implemented have resulted in the underachievement of the intended objectives and rejection of some of the imposed solutions.

The present study proposed a novel MCDA procedure for evaluating and selecting feasible and infeasible choices from the shortlist that emerged from the GP technique and MAVT model applications. The model combined two techniques; the GP technique and the MAVT technique. The framework proved useful in solving a multi-objective combinatorial problem optimally while using a consensus-driven and interactive decision-making process.

The study explains how the augmented Chebychev GP and the MAVT models can be adopted and adapted to help tackle the complexities of policy analysis and implementation of programmes to ensure access to energy by the poor. A discussion of how a decision-maker utilises the framework developed under the different scenarios were also included.

The scientific contributions of the study go beyond the MCDA framework developed as it also tackles the quantitative and qualitative policy impact and examines the various strategies for defending the decisions to the press, academia, beneficiaries, taxpayers and political principals. The scientific contributions of the present study are not targeted only to decision-makers but also to scholars working on empirical or theoretical research using quantitative and qualitative policy modelling and evaluation techniques.

The study contributions are also intended for technical experts and analysts from stakeholder organisations involved in formulating and implementing policies to reduce energy poverty. The author's work in developing the augmented Chebychev GP model and the value function model and applying it to a hypothetical energy access problem has clear implications for practice.

The study also amplifies the need for home-grown solutions for tackling local problems. This magnification can be achieved by promoting the development of tailor-made MCDA-based procedures to evaluate energy access interventions. Empirical literature supports the need for homemade solutions (Debnath et al., 2018). Most models aimed at addressing the energy access problem originate from developed countries, which means they may not be as useful in developing countries. This condition, therefore, suggests that there is a need for the development of home-grown and tailor-made models that will support the decision-making processes. The nature and complexity of problems differ based on climatic, economic and other factors. Intrinsicly, researchers and scholars are therefore encouraged to confront energy access problems using novel decision-making frameworks.

8.9 Recommendations for future research

In future, the author intends to deepen this research and analysis in South Africa, working closely with actors and stakeholders in the energy ecosystem to help them understand energy portfolios emanating from the study and develop enhanced strategies for activating desired consumer behaviour. The section presents some possible recommendations for further research.

- While the government has made inroads in addressing energy poverty, the study calls for an ex-post assessment of the existing pro-poor energy policies (refer to Table 21), looking at their implementation, impact and effectiveness. The exploration of a deeper understanding of the failure and success stories of the pro-poor policies and strategies implemented to date should be central to any future research into this topic. A suggested approach would be to evaluate the impact of the pro-poor energy policies with regards to their implementation, measure the effectiveness of the policies and evaluate the outcomes of these policies measured against envisaged goals.
- This research was carried out at a time when the energy sector was undergoing significant changes. These developments include the ongoing debate on climate change, shifting technological learning curves and regulatory changes. Future research can examine the occurrence and influence of these developments.

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- This research focused on one aspect of poverty among low-income communities. Yet, communities living in low-income areas are also confronted with other vices such as crime and poor access to potable water and decent sanitation. A possible suggestion for future research would be to apply the framework developed for the study to a water access problem. A suggested approach would be to follow a similar framework used in this study to assess optimal portfolios for the supply of energy among low-income communities.
 - The portfolios and scenarios presented in this research are based on hypothetical case studies. The framework developed for the study can be used to address the methodological challenges for modelling energy access problems among low-income communities. There is also scope for empirical investigations of the energy access problem among low-income communities in South Africa and other developing or under-developed counties. A recommended approach would be to expand the framework developed to real-life policy scenarios and problems.

Energy will continue to be critical for economic development and social wellbeing and therefore understanding the links between the two is of utmost importance. It is hoped that this research provided a foundation for further research into this policy issue of contemporary importance. It is advised that future studies need to focus on the user dimension of energy poverty, stressing the role of users of proposed technologies not only as consumers but also as producers of solutions to tackle energy poverty. It is hoped that this research demonstrated that isolated human actions do not have isolated consequences; that an integrated and holistic approach may lead to better and more sustainable outcomes for the greater good of society.

APPENDIX A: FUEL PROPERTIES

Table 22: Calorific values of various fuels

Carrier	Calorific unit value	Calorific value
LPG	MJ/l	26.7
Kerosene	MJ/l	37.5
Diesel	MJ/m ³	38.1
Coal Eskom Average	MJ/kg	20.1
Biomass (wood dry typical)	MJ/kg	17.0

Source: Department of Energy (2018)

APPENDIX B: UNIT CONVERSIONS

Table 23: Energy unit conversion factors

From \ To	J	kWh	Ton of oil equivalent	Btu
1J	1	0.278×10^{-6}	0.2388×10^{-6}	0.948×10^{-3}
1 kWh	3.6×10^6	1	0.86×10^{-6}	3.412×10^3
1toe	42×10^9	11630	1	39.68×10^6
1 Btu	1.055×10^3	0.293×10^{-3}	0.252×10^{-9}	1

Source: Department of Energy (2018)

Table 24: Unit prefixes

Prefix	Symbol	Power
Kilo	K	10^3
Mega	M	10^6
Giga	G	10^9
Tera	T	10^{12}
Peta	P	10^{15}
Exa	E	10^{18}

Source: Department of Energy (2018)

APPENDIX C: SUMMARY OF ENERGY PORTFOLIOS

Energy source	GP portfolio	GP portfolio	MAVT Portfolio	MAVT Portfolio
	[Rural area]	[Informal urban area]	[Rural area]	[Informal urban area]
Firewood	0%	20%	0%	5%
Kerosene	0%	2%	0%	0%
Bioethanol fuel	22%	23%	5%	25%
LPG	20%	19%	20%	25%
CCGT	5%	0%	5%	0%
Solar PV	29%	34%	30%	25%
Solar with Storage	0%	0%	15%	20%
Wind	23%	0%	25%	0%

Source: Augmented Chebychev GP model, MAVT model

APPENDIX D: A PRACTICAL GUIDE TO THE V.I.S.A GROUPWARE PACKAGE

This guide has been prepared to assist users of the MAVT model developed with problem structuring and problem-solving using the V.I.S.A groupware. By following the steps in this guide, users should be able to set up V.I.S.A models and solve MCDA problems in the public policy decision environment. The V.I.S.A groupware, developed by Belton (1990), is a transparent software that helps analysts and decision-maker(s) to develop, organise and synthesise information during the decision-making process. The groupware enables users to gain insights about a problem and provides the means for justifying and explaining the reasoning and rationale behind a decision taken. The guide draws from the MCDA literature with adaptations from Belton (1990); Belton and Stewart (2002); Rosenhead and Mingers (2004) and Eden and Ackermann (2006), (Refer also to Section 3.1.1 and Figure 12).

MCDA and V.I.S.A methodological steps:

Step 1: Problem identification and formulation

- This is the first step in MCDA. The software is timesaving and designed to capture data and information sensibly and logically when assessing the best portfolio.
- It is advisable to develop a range of alternatives in consultation with the decision-maker(s). In the absence of decision-maker(s), a decision-maker proxy can be developed in the form of a panel of experts drawn from various backgrounds.
- It is expected that their views will be representative of the decision-maker(s) and users to be affected by the policy.
- Use relevant sources for quantitative data and the decision-maker serves as the source for qualitative data.

Step 2: Problem structuring

- **Identifying criteria**
 - Again, in consultation with the decision-maker(s) or a panel of experts, the second step is to develop a value tree (refer to 7.1.2 and Figure 30). A value tree shows hierarchically how alternatives will be assessed.
 - The brainstorming technique is recommended for eliciting criteria. Brainstorming is possible even without alternatives in place.

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- In some instances, it is possible that criteria cannot be easily developed despite the alternatives being known. To solve this problem, three methods are recommended (See Belton, 1990) recommends the following three methods:
 - Where a single alternative is known, the plus-minus-interesting points method²⁸ ;
 - Where two alternatives are known, the pairwise comparisons method;
 - Where three alternatives are known, the repertory grid method²⁹.
 - The user needs to be aware of pre-emptive. Pre-emptive criteria are only used to screen alternatives and need not be included in the value tree.
 - The user needs to be aware of differentiating and non-differentiating criteria. Differentiating criteria is used in cases where the decision to be made relates to ranking alternatives and should be excluded from the value tree.
 - The user needs to strike a balance reading the level of detail in a value tree. A value tree should be developed in such a way that the level of detail is appropriate to the problem at hand and avoids double counting According to Belton (1990) a value tree should not use more than two criteria that measure the same attribute as this will amount to double counting.
 - Belton (1990) also recommends the use of proxy variables in cases where it is difficult to measure a criterion and criteria used in a value tree should satisfy preference independence condition.
 - The user needs to also ensure that in the process of developing a value tree, the value tree needs to be appropriate and meets five attributes as posited by Keeney and Raiffa (1976, 1993). All criteria in a value tree must be complete; operational, decomposable, non-redundant and should be of a minimum size (see also Keeney and Raiffa,1976; Goodwin and Wright, 1991).

- **Identifying alternatives**

- In consultation with the decision-maker(s) or a panel of experts, once the criteria for evaluating alternatives has been set up, the next step is to identify alternatives. The user should investigate and establish the existence of possible hidden alternatives. Further research in consultation with the panel of division-maker(s) or panel of experts is recommended.

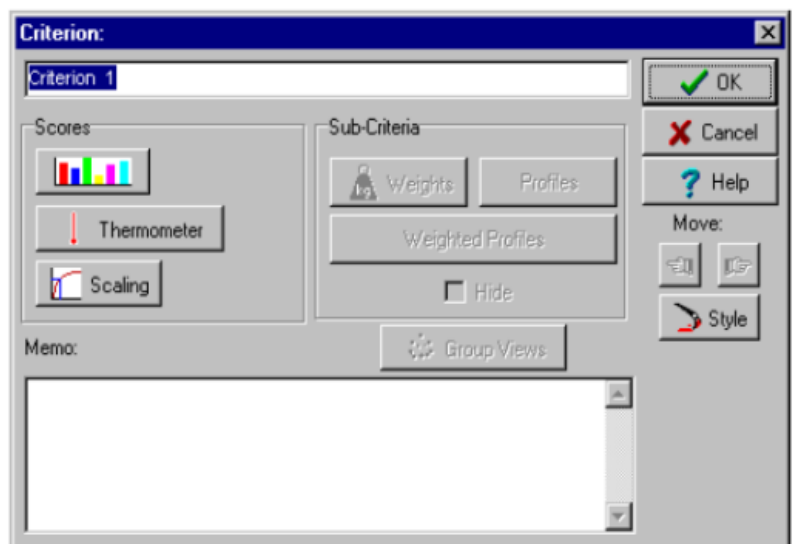
²⁸ Plus, minus, interesting is a brainstorming, decision-making and critical thinking tool. It is used to encourage the examination of ideas, concepts and experiences from more than one perspective (de Bono, 1986).

²⁹ The repertory grid is a method for identifying the ways that a decision-maker construes (interprets or gives meaning to) his or her experience.

- The decision-maker(s) or their proxies needs to be satisfied that the elicited alternatives are appropriate and represents all possible solution options.
- A screening process can be used to further reduce the size of alternatives for further evaluation. The GP technique is recommended given its ability to handle large sets of alternatives. This is important as the smaller the set of alternatives, the more manageable they are especially when faced with financial and time constraints.
- The user needs to ensure that there are no overlapping alternatives, and the final set of alternatives must be mutually exclusive (independent) of each other.

Step 3: Using V.I.S.A groupware

- Users of the V.I.S.A software are encouraged to make use of the demo models and tutorials that provide users with step-by-step instructions and examples on how to open and save new and existing V.I.S.A files.
- **Developing a value tree in V.I.S.A**
 - This is the first step. A value tree in V.I.S.A is developed by right-clicking anywhere on the landing window - a new criteria creation window will pop up and this will automatically be tethered to the overall criterion.
 - All subsequent criteria to be created will also automatically be linked to the overall criteria. Linking two criteria together is achieved by right-clicking and holding the child-criterion and then dragging the cursor to the parent criterion and then releasing the cursor at the end.
 - Renaming criteria is achieved by left clicking on the criteria window and typing a new name in the open dialog box (an illustration of the dialog box is provided on the right). Additional information and data can be added to the dialog box.



- Clicking the “bomb” icon will delete a criterion and this is accompanied by a warning that if a child criterion exists, it will also be deleted.
- For easy observation and visibility of the value tree, use the “tidy tree” feature and “Zoom in” button to automatically clean up and magnify the value tree. Tidying up the value tree can also be done manually.

- **Capturing alternatives**

- Alternatives are captured by entering information in the “Alternative window” (See illustration).
- Use the Alternative/Add button located at the main menu bar to add new alternatives. A short-cut key (Ctrl-A) can also be used to add new alternatives
- Changing the name of an alternatives entails clicking on an alternative and editing the name in the dialog box.

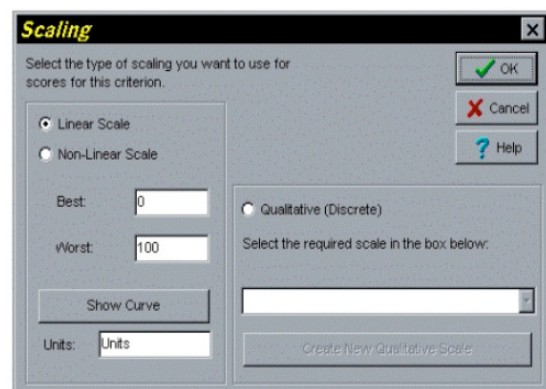
	Criterion 2	Criterion 3	Criterion 4
Alternative 1	0	0	0
Alternative 2	0	0	0
Alternative 3	0	0	0
Alternative 4	0	0	0

- **Scoring alternatives**

- This is a critical stage in MCDA. The decision-maker(s) needs to be sufficiently informed, understands the problems fully and feel ready to define and a scoring system to be used for the performance evaluation of all criteria against the corresponding set criteria.
- Scoring entails assigning values to each alternative to enable the decision-maker(s) to gauge and ponder on the importance of each option under each child criterion.
 - Alternatives are scored by decision-maker(s) using an interval scale. (Goodwin and Wright, 1991).
 - The V.I.S.A groupware package supports interval scaling (0 to 100) for the scoring of alternatives, and this is achieved through the use of local or local interval scales (refer to 7.1.3 and see also Belton, 1990).
- The information or data being used is a key determinant of the scale to be used. For quantitative data, it is recommended to use either global or local scales.

For qualitative data and information, local scales are recommended given their simplicity.

- It is strongly encouraged to choose a scoring method that a user is most comfortable with. This is important as it will make the process of assigning weights much easier later down the road. Weights partially depend on the selected scoring scales.
- The present study made use of both local and global scales. Global scales require more thought than the local scales at the scoring stage. The author found the global users to be easier to work with especially when one gets to the point of assigning weights. An extensive guide and description of the two scoring methods is found in Goodwin and Wright (1991), also refer to Section 7.1.3.
- The V.I.S.A groupware package has a built-in qualitative scoring system available for users however it also provides an option for users to develop their scoring system.
- Users are required to define scales in such a way that it is clear that “more” is “best” which means assigning a bigger value of 100 if it’s the case as more is not always the best. In some instances, costs as an example, “less” is best. These terms need to be properly defined and explained to the decision-maker from the onset and throughout the decision-making process.
- Users should endeavour to make use of natural scales in which more is given a high value and still performs worst in V.I.S.A score even though it is "worse".
- This is achieved by the use of the reverse scales feature in V.I.S.A and this can be done directly during the scoring process, but this must be done in consultation with the decision-maker and the type of model in use.
- Reversing scaling is achieved by left-clicking on the end-criterion and selecting the scaling icon then changing the “worst” box from 0 to 100 “and the “best” box from 100 to 0.



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- Please note that all scales used in the V.I.S.A groupware are linear by default. To change from linear to non-linear scales first click the criterion to be changed, click the Scaling button and then select the Non-Linear Scale option. The required shape is obtained by clicking and dragging the line until the desired shape has been attained.
 - Make use of the view Profiles chart to assess the effect of reversing scales on the criteria scores. This is important to avoid the wrong interpretation of the results.
 - To enter scores in the V.I.S.A groupware package, follow any of the four steps below:
 - Option 1: Use the Thermometer feature, left click and drag the selected alternative until the desired position has been reached. The process is repeated for all the remaining alternatives. This is probably the easiest way to enter scores.
 - Option 2: Use the Bar chart feature, left click and drag the selected alternative until the desired position has been reached. The process is repeated for all the remaining alternatives.
 - Option 3: Use the Alternatives window and capture data directly.
 - Option 4: Use the Import Data feature. Using this feature, data can be directly imported from a Ms Excel spreadsheet. To import data, ensure that the data is saved in text tab-delimited (.txt) or comma-separated values(.csv) format while also making certain that cell A1 is left blank.
 - Criteria heading must be captured in the first row, alternative names in column A and data in the second row. This is repeated from Column B onwards. To avoid conflict, the Ms Excel file must be closed before opening it using the VISA software package.

- **Weighting**

- This is a critical step. For the V.I.S.A groupware to compute the overall score, the user, in consultation with the decision-maker (s) must place weights on all parent criteria. Weights represent the relative importance and intrinsic worth of each child criteria on the parent criteria's score.
- The author recommends the use of the swing weights method (Goodwin and Wright, 1991) for determining weights (Belton, 1990, see also section 7.1.3)

-
- The user is encouraged to make use of the Profiles chart before capturing weights as the chart shows in detail the best and worst options on different criteria graphically.
 - First, open the parent criterion dialog linked to the children criteria weights you wish to enter or change. The dialog box is opened by left clicking on the criterion.
 - To input and assess weights in the V.I.S.A groupware package, follow any of the two steps below:
 - Option 1: Position the cursor at the top of the menu bar and drag the weight until the desired position is reached.
 - Option 2: Select the Settings menu and input the weights numerically by clicking on the required value of the weight.
 - *Caution: do not click anywhere in the weights bar during the process of capturing or amending weights and this may result in the accidental change of weights.*
 - Weights can be fixed in V.I.S.A groupware package and this can be achieved by simply right-clicking on the desired criterion, a red name will appear to show that the weight has been fixed. Right-clicking again will free the weight.
 - The V.I.S.A groupware package allows a user to equalise weights. Except for fixed weights, right-clicking anywhere on a weight window automatically equalises weights in a family and all the weights are changed to one.
 - The user is encouraged to frequently save the model such that if one makes a mistake, one can easily revert to a previously saved file and restore the weights. The built-in V.I.S.A screenshot feature is very useful. V.I.S.A groupware package also comes with a Snapshot feature that allows a user to save different versions of the weights during the decision-making process.
 - **Results and analysis**
 - The best and recommended way to visualise the V.I.S.A model results and make judgments on the best alternative is through the use of the Thermometer and Bar Chart options
 - To display V.I.S.A model results, click the “Overall Score” criterion button and select either the Thermometer or Bar Chart option.
 - The Thermometer and Bar Chart options should be viewed as a first step when analysing results. Further analysis of the results will need to be conducted

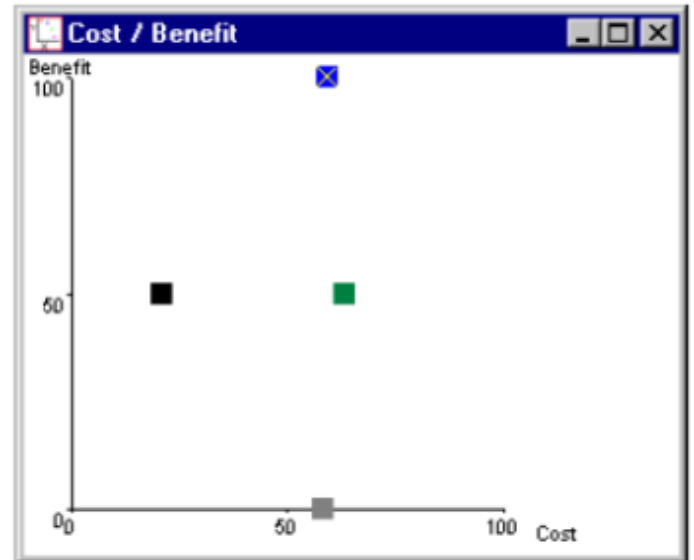
using the X-Y plot. The X-Y plot displays the relative efficiency of one alternative over another and is useful for highlighting trade-offs between two criteria (See Figure 32 and Figure 35).

- The procedure for creating an X-Y plot is detailed below:

- First, click on the X-axis button and move the cursor to the desired X-axis criterion.

- Second, click on the Y-axis button and move the cursor to the desired Y-axis criterion.

- Third, select the “Create X-Y Performance Graph” feature and the V.I.S.A groupware will display the results in the form of an X-Y graph.



- The X-Y graph enables the user and decision-maker(s) to gain a better understanding of the problem and solution at hand.

- The X-Y graph also enables the user and the decision-maker(s) to identify dominated alternatives. An alternative is said to be dominated when another solution option scores better on every criterion. All dominated alternatives must be excluded from further analysis.

- Belton (1999) encourages users to be aware of the “linearity trap”. In a linearity trap, an alternative can be excluded from the efficient frontier but has a better better-balanced decision from that those included simply because the other alternatives are more extreme.

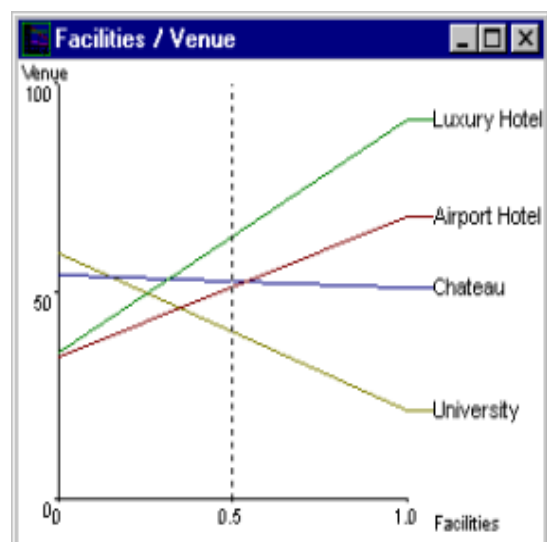
- Users are encouraged to score all criteria on all levels before declaring an alternative to be “dominated”.

- **Sensitivity Analysis**

- The V.I.S.A groupware package has a built-in sensitivity analysis feature. This feature is important and the purpose of conducting a sensitivity analysis during the decision-making process is to test the robustness of a model and prevent the making of wrong decisions.

- Sensitivity analysis also presents the decision-maker(s) with an opportunity to fully comprehend the decision at hand and the implications of altering the modelled variables influencing the decision.
- The procedure for conducting sensitivity analysis using the V.I.S.A groupware is detailed below:
 - The user must first establish and ensure that the model is working correctly.
 - Second, the user must be satisfied that the overall score appears reasonable in retrospect. If the decision appears unreasonable, double-check the scoring and weights of the model.
 - Third, the user must be satisfied that the preferred alternative is clear. Close options must be investigated further, and the user may need to group the alternatives if there are too many close options. This also enables the decision-maker(s) to learn even more about the problem.
 - Fourth, once the user is clear on the above, leave the Thermometer, Bar Chart and the X-Y plot on the screen and pick on any parent criteria, then select the Weights option.
 - Fifth, the weights can then be changed by interactively changing the weights in the Weights window focusing on the extremes. Continually check the results for any changes in the best alternative.
- The V.I.S.A groupware package contains several built-in Sensitivity Analysis features, and these are summarised below:

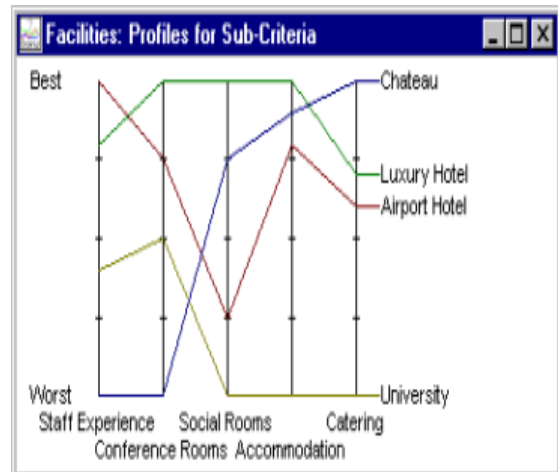
- The **Weight Sensitivity Graph** is used to show the effect of changing weights on aggregated scores on the selected level.
- To create a Sensitivity Graph:
 - Click the “Choose Weight for Weight Sensitivity Graph” button and move the cursor to the child criterion whose weight is to be altered and



click again. Next, click on the “Choose Score for Weight Sensitivity Graph” button.

- Select the criterion whose score is to be observed using the cursor by clicking on it. Note that this only applies to parent and grandparent criteria.
- To view the graph, click the “Create Weight Sensitivity Graph”.

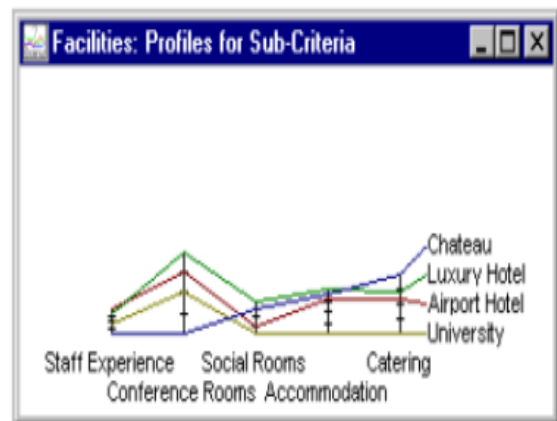
- The **Profiles chart** is used to show the profile of scores for each option on all child criteria



- To create a Profile of the child criteria:

- Click on any parent criterion and select Profiles in the dialog box that appears.

- The **Weighted Profiles chart** is used to show the weighted profile of scores for each option on all child criteria



- To create a Weighted Profile of the child criteria:

- Click on any parent criterion and select Weighted Profiles in the dialog box that appears.

- **Data Envelopment Analysis:**

- An additional and useful feature of the V.I.S.A software is the built-in DEA package that is installed as an add-in. DEA enables users to measure the relative efficiency of an alternative over another. This is a useful tool for conducting Sensitivity Analysis in an input/output model. (refer to Section 3.3.2.2).

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- The procedure conducting Sensitivity Analysis using the DEA feature in V.I.S.A is detailed below:
 - Create an X-Y plot as discussed earlier and save the model. The DEA feature will spontaneously change the weights.
 - Right-click on any option – the DEA tool will then automatically determine whether or not an alternative can be migrated to the efficient frontier.
 - In closing, it is advisable to continually save the V.I.S.A model and use the Snapshot feature as the V.I.S.A software does not automatically save the sensitivity analysis charts upon changing the weights.
 - It is also advisable to continually analyse each graph and chart after changing weights. Moreover, ensure that the graph contains the effected changes. Regrettably, you will need to start the sensitivity procedure all over again if it appears that the graph is not responding to effected changes to obtain the correct results.

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